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Environmental impacts of vegetables consumption in the UK

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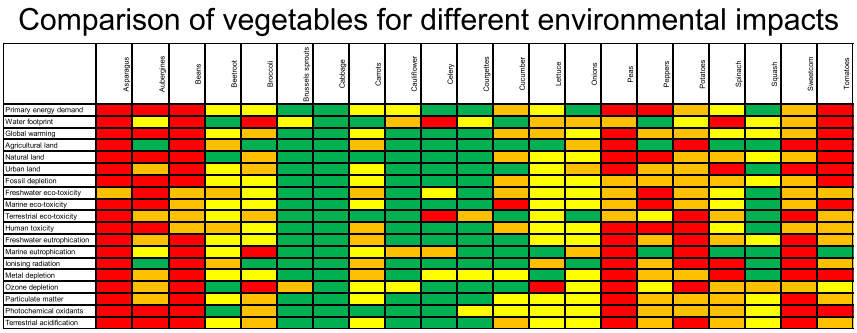
HIGHLIGHTS

- Life cycle impacts are assessed for 56 vegetable products consumed in the UK.
- Asparagus has the highest impacts across most of the 19 impact categories considered.
- Cabbage, celery and Brussels sprouts are environmentally most sustainable.
- Vegetables consumption generates 20.3 Mt CO_2 eq. and depletes 253 Mt eq. water/yr.
- Air-freighted fresh vegetables have five times higher impacts than UK-grown produce.

GRAPHICAL ABSTRACT



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ABSTRACT

A healthy diet depends on the daily intake of vegetables. Yet, their environmental impacts along the full supply chains are scarcely known. Therefore, this paper provides for the first time a comprehensive evaluation of the life cycle environmental impacts of vegetables consumed in UK. The impacts are assessed for 56 fresh and processed products produced domestically and imported from abroad, considering both the product and sectoral levels. At the product level, taking into account the market mix of fresh and processed vegetables for each vegetable type sold in the UK, asparagus has the highest per-kg impacts across most of the 19 impact categories considered, while cabbage, celery and Brussels sprouts are generally environmentally most sustainable. At the sectoral level, the annual consumption of 10.8 t of vegetables generates 20.3 Mt CO_2 eq., consumes 260.7 PJ of primary energy and depletes 253 Mt eq. of water. The majority of the impacts are caused by potatoes since they account for 56% of the total amount of vegetables consumed, with crisps and frozen chips contributing most to the total impacts. Importing vegetables grown in unheated greenhouses in Europe has a lower impact than UK vegetables cultivated in heated greenhouses, despite the transportation. The impacts of air-freighted fresh vegetables are around five times higher than of those produced domestically. Even processed products have lower impacts than fresh air-freighted produce. Packaging also contributes significantly to the impacts, in particular glass jars and metal cans used for processed vegetables. Other significant hotspots are open display cabinets at the retailer and cooking of vegetables at home. The results of this study will be useful for food manufacturers, retailers and consumers, helping to identify improvement opportunities along vegetables supply chains.

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1. Introduction

Being a source of essential nutrients, vegetables are crucial for a healthy diet. Diets with a lower content of vegetables are associated with an increased risk of cardiovascular diseases, type 2 diabetes, cancer

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and obesity (Gakidou et al., 2017). Studies also show that a high vegetable diet can reduce premature deaths (Oyebode et al., 2014; Wang et al., 2014). Therefore, health organisations, such as WHO, promote a minimum daily intake of vegetables and fruits of 400 g per person (FAO/WHO, 2004). Both fresh and processed vegetables, including frozen, canned and pickled vegetables, can be consumed to meet the guidelines for a healthy diet.

Sustainable dietary choices also involve consideration of environmental impacts of food products (Macdiarmid et al., 2011). Although vegetables are perceived to have lower environmental impacts than meat and dairy products (Sonesson et al., 2010), their impacts will depend on various factors. For instance, the difference in impacts between locally grown and imported vegetables is not obvious as heated greenhouses may have higher impacts than transportation, or vice versa (Carlsson-Kanyama, 1998). Therefore, it is important to consider the complete supply chains of vegetables to determine their environmental impacts.

A number of studies have been published on the life cycle environmental impacts of different types of vegetable. Among these, tomatoes have been analysed most extensively (Heller et al., 2016). Several papers have focused on farm production, comparing different farming practices, such as open field and greenhouse cultivation (Tamburini et al., 2015; Zarei et al., 2018). Others have examined how to improve the latter (Hendricks, 2012; Williams et al., 2006). Some publications have gone beyond the farm gate to consider other life cycle stages, such as packaging and transportation (Cellura et al., 2012; Fuentes et al., 2006; Pydynkowski, 2008). Several authors have also examined the impacts of local production of tomatoes in comparison with the imported produce (Carlsson-Kanyama, 1998; Payen et al., 2015; Theurl et al., 2014).

Studies of other vegetables include potatoes, lettuce and carrots; however, they are mainly limited to greenhouse gas emissions (GHG) and the related global warming potential (GWP) (Fuentes et al., 2006; González et al., 2011; Hospido et al., 2009; Röös and Karlsson, 2013; Williams et al., 2008). Those that have considered additional impacts, such as energy use, eutrophication and acidification, have been limited to few life cycle stages or to a certain country. Regarding the latter, GHG emissions of various fresh vegetables have been estimated for the Swedish and Swiss supply chains (Davis et al., 2011; Stoessel et al., 2012). GHG emissions have also been determined for some UK vegetables (Audsley et al., 2009); however, beyond GWP, no other impacts have been considered and the study focused mostly on fresh vegetables, excluding management of packaging waste.

The impacts of frozen vegetables have been evaluated previously for broccoli and carrots in comparison with their fresh counterparts (Gottfridsson, 2013; Milà i Canals et al., 2008). However, studies of canned vegetables are rare and focus predominantly on one type of vegetable (Del Borghi et al., 2014; Garofalo et al., 2017; Sachakamol and Ngarmsa-ard, 2015). Some publications are available on processed potato products (Mouron et al., 2016; Nilsson et al., 2011; Ponsioen and Blonk, 2011), but are again mainly limited to GWP and specific to the Dutch or Swiss supply chains. Generally, publications on processed vegetables are scarce.

To the authors' knowledge, life cycle assessment (LCA) studies of complete supply chains of vegetables considering fresh and processed produce have not been published yet for any country or region. This paper focuses on the UK vegetables market and aims to provide a comprehensive analysis of environmental impacts of the whole sector considering the complete life cycle of 21 vegetable types consumed in the UK. This includes farm production, curing, storage, processing, packaging, transportation, retail, consumption and management of food and packaging waste as well as wastewater treatment. Both fresh and processed vegetables are considered, including frozen, pickled, canned, fried and dried vegetables. Overall, 56 vegetable products are evaluated, considering both home-grown and imported produce as well as various transportation modes. In total, 19 impacts are estimated, including GWP, land use, eutrophication, acidification, primary energy demand and water footprint. The impacts are assessed at the product and sectoral levels, for the latter taking into account the annual consumption and the contribution of various vegetables to the overall impacts.

2. Methods

The LCA has been carried out following the ISO 14040/14044 guidelines (ISO, 2006a, 2006b). The goal and scope of the study are described below, followed by the inventory data and the impact assessment method in the subsequent sections. Prior to that, the next section provides an overview of the UK vegetables market.

2.1. An overview of the UK vegetables market

Vegetables are the largest food group consumed in the UK with an estimated total of 10.8 Mt sold annually (DEFRA, 2015; ITC, 2015). The market is worth £12.5 bn/yr and represents 16% of the total household expenditure on food (DEFRA, 2014a, 2014b). Asparagus is the most expensive produce (£3.29–4.77/kg), followed by imported fresh beans and peas (£2.24–2.60/kg), while root vegetables and domestic legumes are the least costly (£0.13–0.54/kg) (DEFRA, 2014a, 2014b).

A breakdown of different types of vegetables sold in the UK is given in Table 1, together with the share of domestic and imported produce. Potatoes are by far the largest sub-sector, accounting for 56% of the total vegetables consumption, followed by carrots (8%), onions (7%) and tomatoes (5%). The majority of vegetables (72%) are produced domestically, with the rest imported from across the globe. However, the proportion of imported vegetables increases to 49% when potatoes are excluded. Furthermore, the imported quantities vary with the type of vegetable. For instance, while the UK is nearly self-sufficient in carrots and cabbage production, more than 80% of tomatoes, bell peppers, aubergines and courgettes are imported. Moreover, all haricot beans used in baked beans are imported.

Processed vegetables originate from various countries. For instance, 94% of beans and legumes are imported due to the high consumption of baked beans which are not produced in the UK. While 30% of green beans are cultivated domestically, all dried and canned pulses are imported. Furthermore, fresh UK tomatoes are grown in heated greenhouses, accounting for 18% of the total fresh tomatoes, with the rest being imported. However, processed tomatoes are sourced entirely from Mediterranean countries. In the case of ketchup, 30% is produced in the UK, with the majority of the rest imported from the Netherlands. However, the ketchup base is tomato paste, which is sourced entirely from the Mediterranean region.

It should be noted that tomatoes, cucumber, bell peppers, courgettes and squash are considered vegetables as they are utilised in cooking as such, although they are categorised botanically as fruits. Potatoes are classified as starches by nutritionists; however, scientifically they are considered a vegetable and hence the latter classification is used in this work.

2.2. Goal and scope of the study

The goal of the study is to assess the environmental impacts of vegetables consumed in the UK on a life cycle basis, considering both the individual products and the whole sector. In total, 21 types of vegetable and 56 products are evaluated here, considering fresh, frozen, canned, pickled and dried products (Table 1), as well as processed products, such as tomato paste, ketchup, chips and crisps. This represents 97% of the vegetables consumed in the UK. The remaining 3% are excluded as they each represent less than 2% of total annual consumption. These are: mushrooms, artichokes and radish. Mushrooms are also excluded due to a lack of data for farm production. For other minor vegetables, there are no data on consumption in the UK and hence they are not considered.

To estimate the impacts at both the product and sectoral levels, two functional units are considered:

Table 1
An overview of the vegetables sector in the UK.

Vegetable	Total[a] (t/yr)	Imported[b] (%)	Imported from[c] (%)	Sold as fresh (%)	Sold as processed (%)	Notes
Asparagus	18,705	74%	Peru (58%), ES (14%), Mexico (10%)	50%	Frozen (24%), canned & bottled (26%)	Includes green and white asparagus.
Beans	476,058	94%	Fresh: KY (56%), ES (8%), Frozen: BE (61%), FR (19%), Pulses: CA (43%), USA (39%)	13%	Frozen green (2%), canned green (5%), dried (4%), canned pulses (8%), frozen pulses (1%), canned baked beans (67%)	Green beans are consumed unshelled, whereas navy beans for baked beans and kidney beans are sold shelled.
Bell peppers	190,926	88%	NL (57%), ES (30%)	92%	Pickled (8%)	
Beetroot	76,221	18%	ES (30%), NL (29%), FR (16%), PT (6%)	97%	Pickled (3%)	
Brussels sprouts	65,828	25%	GR (46%), NL (33%)	77%	Frozen (23%)	
Cabbage	242,759	10%	NL (74%), ES (9%)	81%	Processed (10%), pickled (9%)	
Carrots & turnips	861,989	4%	IS (31%), FR (28%), NL (14%), IT (10%)	81%	Frozen (6%), canned (5%), processed (3%)	
Cauliflower & broccoli	336,566	67%	ES (80%), FR (12%)	85% 36%	Frozen (8%), processed (7%) Frozen (29%), processed (35%)	Cauliflower and broccoli are classified under the same category in the statistical data (DEFRA, 2015; ITC, 2015). However, as cauliflower is cultivated all year round in the UK and broccoli grows only during the summer and autumn months, it is assumed that the share of imported cauliflower is smaller compared to broccoli: 25% compared to 69% for broccoli.
Celery	130,079	60%	ES (96%)	100%		
Courgettes & aubergines	85,794	81%	ES (78%), NL (11%) NL (48%), ES (35%), KY (5%)	100%	–	
Cucumber	192,966	70%	NL (53%), ES (40%)	94%	Pickled (6%)	
Lettuce	296,420	59%	ES (70%), FR (12%)	62%	Processed (38%)	
Onions	790,957	54%	NL (43%), ES (31%), PL (9%)	92%	Frozen (6%), pickled (2%)	
Peas	335,158	36%	Fresh: GT (34%), Peru (16%), ZI (13%), KY (12%); Frozen: BE (53%), ES (13%); Dry: UA (37%), FR (26%), CA (10%)	8%	Frozen (54%), canned (28%), dried (9%)	Processed peas are only sold shelled and fresh peas unshelled.
Potatoes	6,006,857	30%	Fresh: FR (33%), NL (13%), IS (13%), BE (11%), DE (10%), CR (6%); Processed: NL (63%), BE (28%), DE (6%)	74%	Frozen chips (17%), crisps (10%)	
Spinach	62,033	54%	Fresh: ES (73%), IT (11%); Frozen: BE (44%), ES (30%), FR (12%)	20%	Frozen (19%), canned (61%)	
Squash	81,110	65%	NL (18%), GR (15%), SA (12%), PT (12%), ES (11%)	100%		The category of squash refers to winter squash and pumpkins.
Sweetcorn	34,306	77%	HU (40%), BE (19%), PL (15%), FR (13%)	34%	Frozen (15%), processed (7%), canned (45%)	Sweetcorn comprises corn-on-the-knob and corn without the knob (only the kernels).
Tomatoes	510,117	86%	Fresh: NL (42%), ES (34%); Processed: IT (62%), PT (12%), ES (10%); Ketchup: NL (71%), IT (8%)	46%	Canned & bottled (31%), ketchup (20%), paste (2%)	Tomatoes are preserved as concentrated paste, ketchup or in cans and glass jars.

[a] Estimation based on UK production, imports and exports in 2013 (DEFRA, 2015; ITC, 2015).
[b] The imported quantities are shown as average percentages for each vegetable category. Cut-off criterion for imported vegetables is 5%, not including exporter countries where the quantity of vegetables sourced from these countries is below 5%.
[c] Source: (ITC, 2015). ES: Spain, KY: Kenya, BE: Belgium, FR: France, CA: Canada, NL: The Netherlands, PT: Portugal, GR: Greece, IS: Israel, IT: Italy, PL: Poland, GT: Guatemala, ZI: Zimbabwe, DE: Germany, CR: Cyprus, SA: South Africa, HU: Hungary.

- product level: 1 kg of fresh or processed vegetables; and
- sectoral level: annual consumption of all vegetables in the UK.

The scope of the study is from cradle to grave as shown in Fig. 1, comprising farm production, storage, curing, processing, packaging, retail and household preparation, as well as transport and waste management along the supply chain. These life cycle stages are described in more detail in the next section.

2.3. Inventory data and assumptions

2.3.1. Farm production

The inventory data for farm production for vegetables are based on the Ecoinvent database v3.3 (Ecoinvent, 2016), modified to represent the actual production processes, depending on the vegetable. For example, the greenhouses in Ecoinvent use oil or coal which have been replaced by natural gas, to reflect the real situation in the UK and the Netherlands; the latter is one of the leading countries from which the UK imports vegetables. The data for greenhouse cultivation have also been modified to distinguish between heated and unheated greenhouses.

Proxy data have been used to fill data gaps. Specifically, cabbage data have been used for Brussels sprouts, courgettes for squash and carrots for beetroot. The farm production of fava beans is used as a proxy for all bean types. Where region specific processes were available in Ecoinvent, the UK production has been approximated by Northern European countries, given the comparable climatic conditions and farming methods. If available, Dutch data have been used in preference to other countries, but also Swiss and French data have been used alternatively. All vegetables are assumed to be farmed using conventional farming, due to a lack of data on the share or organic farming in different countries and lack of LCA data.

Table 2 provides the amounts of fresh vegetables produced at farm needed to produce the final product. These quantities are calculated

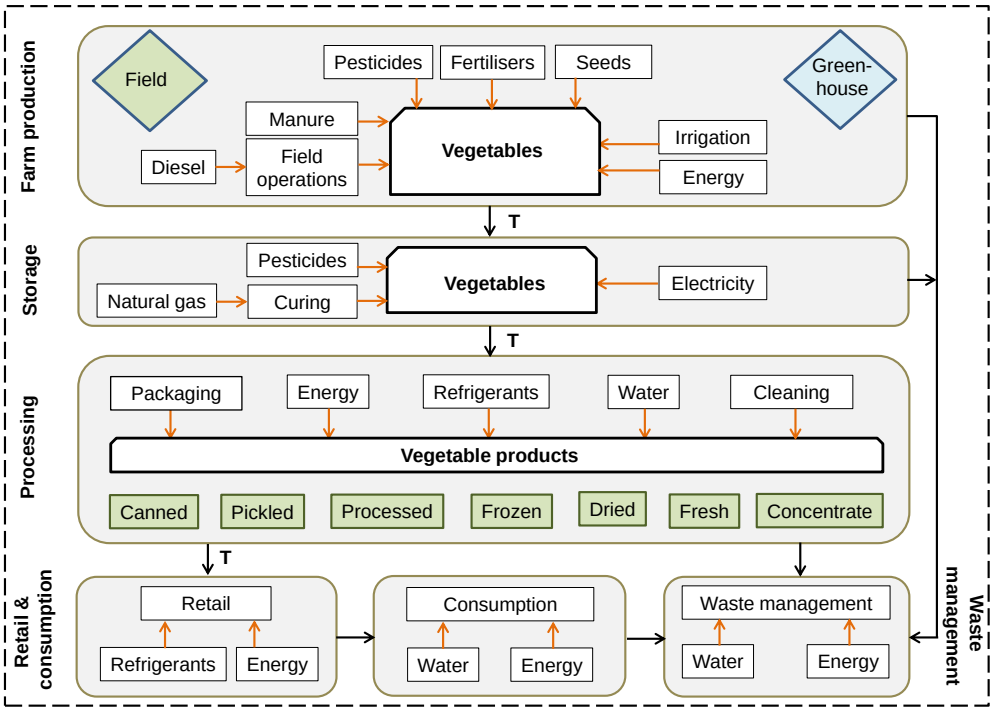


Fig. 1. System boundary and vegetables life cycle stages considered in the study.

based on the dry matter content, loss of moisture during processing as well as the removed shells or cobs.

2.3.2. Storage

To extend their shelf life, vegetables are kept in cold storage several days to several weeks, depending on the type. The data for electricity for storage of various vegetables have been sourced from Stoessel et al. (2012). The missing data for winter squash, celery (stem, not root), sweetcorn, beans, peas, beetroot and Brussels sprouts have been estimated based on the storage temperature and storage period (Table 3).

Furthermore, it is common practice to treat potatoes with the sprout-suppressing pesticide chlorpropham, known commercially as CIPC, before storage. CIPC is applied to approximately 50% of UK's fresh potatoes, at the level of 24 g/kg potatoes (Potato Industry CIPC Stewardship Group (PICSG), 2018). Potatoes used for processing are stored at higher temperatures than the fresh to maintain the frying quality for crisps and chips. Therefore, they need more CIPC than fresh potatoes (42 g/kg).

2.3.3. Curing

Onions and winter squash are cured before storage to ensure that the long storage period does not affect the quality (Downes et al., 2009). During the curing process, forced air drying is used to dry the outer skin of onions and harden the skin of winter squash. Curing of onions is carried out in two stages over 3–6 weeks (Assured Produce, 2008; WRAP, 2011). The heat required for curing of onions has been estimated using the equation below and the values in Table 4:

$$Q = V \cdot t \cdot \rho \cdot c_p \cdot \Delta T \quad (1)$$

where:

Q energy for curing a produce (MJ/kg)
V air flow rate (m^3/hr·kg)
t duration of curing (hr)
ρ density of produce (kg/m^3)
c_p specific heat capacity (kJ/kg·K)
ΔT temperature difference during curing (K).

Table 2
Amount of fresh vegetables at farm required for the final product.

Final product	Amount of fresh produce at farm (kg_{fresh}/kg_{final})	Comment	Reference
Sweetcorn kernels	1.77	Cob mass: 43%	(Geeta et al., 2017)
Fresh green beans unshelled	0.1	Dry matter in green beans: 8.7%	(Finglas et al., 2015)
Shelled bean pulses	2	Shell proportion: 50%	(Finglas et al., 2015; USDA, 2015)
Fresh peas unshelled	0.29	Dry matter in fresh peas: 25.4%	(Finglas et al., 2015)
Fresh peas shelled	0.73	Shell mass: 60%	(Finglas et al., 2015; USDA, 2015)
Canned pulses	0.349	The amount of dried pulses to obtain 1 kg of canned pulses, which absorb water during cooking	(Durlinger et al., 2017)
Canned tomatoes	1.81		(Del Borghi et al., 2014; Manfredi and Vignali, 2014)
Tomato ketchup	1.48		(Kraft Heinz group, 2018)
Tomato paste/concentrates	6	Water in fresh tomatoes evaporates	(Fidan and Tanrivermis, 2006)
Tomato passata/puree	2.25		(George DeLallo Company, 2014)
Potato chips	2		(Ponsioen and Blonk, 2011)
Potato crisps	3.25	Due to the thin slices, the majority of water is removed during the frying process	(AHDB and Potato Council, 2015)

Table 3
Storage energy based on Garnett (2006), WRAP (2011), Rizzo and Muratore (2009) and Toivonen and Forney (2004).

Storage energy for vegetables	Storage temperature (°C)	Storage time (days)	Storage energy (MJ/t·day)	Total energy (MJ/kg)
Winter squash	13–18	120	2.7	0.324
Celery (stem, not root)	0–0	56	5.4	0.3024
Sweetcorn	0–1	7	5.4	0.0351
Beans (fresh green)	7–10	21	2.7	0.0567
Peas	0–2	7	5.4	0.0351
Beetroot (as carrots)	0–1	210	5.4	1.13
Brussels sprouts	0–2	30	5.4	0.162
Potatoes, fresh[a]	8–9	215	2.7	0.58
Potatoes, processed[a]	6–13	140	2.3	0.322

[a] Treated with chlorpropham pesticide (CIPC).

Since onions are cured after harvest in summer, it is assumed that the air has a temperature of 20 °C before being heated to the temperatures required as shown in Table 4.

Curing of winter squash is accomplished in a single drying stage over 14 days, with a low air flow rate, requiring less energy than onions (0.3 vs 0.815 MJ/kg).

2.3.4. Processing

Vegetables are sold either as fresh or processed. Fresh vegetables are washed, sorted and packed at packing houses to be then distributed to regional distribution centres (RDC). Energy data for these activities are only available for potatoes, reported at 0.216 MJ/kg of electricity (WRAP, 2014); this value is assumed for electricity consumption at packaging houses for all other fresh vegetables.

Vegetables that are processed further can be sorted into the following categories: pre-prepared, frozen, canned, pickled, dried, concentrates, sauces and potato crisps and chips. The category of 'pre-prepared' includes peeled and cut vegetables, which might be mixed with other vegetables, as in stew and stir-fry packs. The following vegetables are assumed to be included in this category based on market availability: carrots, broccoli, cauliflower, sweetcorn, peas and beans. Apart from washing, sorting and packing, some vegetables are cut into different sizes and others are peeled. The energy for cutting and peeling has been obtained from the Best Available Techniques (BAT) report (European Commission, 2006).

Frozen vegetables require blanching before freezing to inactivate enzymes, which can cause the decay of vegetables even when frozen. During blanching, vegetables are boiled for a short period and cooled down. Therefore, frozen vegetables have been modelled based on the data for processed vegetables, with the additional energy for blanching and freezing (European Commission, 2006). The data on refrigerant leakage have been source from DEFRA (2008).

Canning is another way to preserve vegetables. It involves several processing steps, including washing, cutting, blanching, peeling, pulping, cooking and sterilisation. Blanching, cooking and sterilisation are the most energy-intensive stages in canning. Data on canning for pulses and tomatoes have been sourced from the Agri-footprint database and the BAT report, respectively (Durlinger et al., 2017; European Commission, 2006). For other vegetables, data for the general canning process from Masanet et al. (2008) have been used.

The main processing stages of pickled vegetables are washing, blanching, peeling, cooking, cutting and pasteurising (European Commission, 2006). It is assumed that the pickling process is similar to canning in terms of energy use. Pickled vegetables are prepared with vinegar, salt and sugar to reach desired acidic and salty flavour (European Commission, 2006; Noonari and Memon, 2015). The brine consists of 5% vinegar and 3% of salt and sugar each (FAO, 2007). In pickles and for preservation, the most common vinegars used are spirit and malt with 5% acetic acid. In this study, malt vinegar made of barely grains has been assumed. Energy consumption in vinegar production is not considered due to a lack of data.

Dried legumes are referred to as pulses and are harvested dry with a moisture content of approximately 13%. For better storage, the pulses are dried until a dry matter of 89% is achieved. Data for the drying process have been obtained from Ecoinvent. Pulses are then pre-soaked, cooked and canned. The dried beans absorb the water during soaking and cooking, decreasing the dry matter from 84% to 27%. The quantity of dried pulses is given in Table 2, which is assumed in processing plants for canned pulses, as well as at home for preparing dried pulses. Canned peas can be prepared from dried or fresh peas. It is assumed that half of the purchased canned peas are made from dried peas and the rest are cooked from fresh peas.

Tomatoes are consumed fresh or processed as canned, bottled, paste or ketchup. It is assumed that the canned tomatoes consist of 60% tomatoes and 40% tomato juice from concentrate (Garofalo et al., 2017). Furthermore, bottled tomato products are usually referred to as passata or puree containing lightly cooked tomatoes. Tomato paste is a tomato concentrate, which is also used as the base ingredient for ketchup. The different tomato products contain varying quantities of tomatoes, which are summarised in Table 2. Furthermore, the processed tomato products are entirely made of Mediterranean tomatoes and then imported to the UK. Ketchup is assumed to be produced from tomato paste with a concentration of 32 ^{0}Brix.

All potatoes are washed and grated. Potatoes for processed products are peeled, blanched and sliced. For chips, the sliced potatoes are fried and frozen. The energy for these operations has been obtained Ponsioen and Blonk (2011). Crisps require the same processing steps; however, the energy use is calculated separately since the potato quantity varies and the potato slices are much thinner. The energy for washing, peeling, blanching and slicing has been calculated based on the BAT report (European Commission, 2006). The energy for frying of crisps has been determined assuming a fryer capacity of 2574 kW and a frying time of 3 min (Wu et al., 2012). Both crisps and chips are fried in vegetable oil and they absorb a proportion of oil (Table 5). Crisps contain more oil than chips, as the slices are much thinner and they are deep fried. The energy consumption for the different processing steps is summarised in Table 5.

Cleaning of the equipment is also considered, based on a tomato processing plant (Del Borghi et al., 2014). The following cleaning agents are assumed to be used (per kg of vegetables): sodium hydroxide (0.198 g), hydrochloric acid (0.63 g) and sodium hypochlorite (0.49 g).

2.3.5. Packaging

Both primary and secondary packaging are considered, with the latter assumed to be cardboard across the vegetables. The primary packaging varies with vegetable type. For fresh produce, 30.7% is sold loose in UK stores without any primary packaging, with the majority of the rest packaged in different plastic packaging (Garnett, 2006). Fresh,

Table 4
Curing process parameters and energy consumption for onions based on WRAP and Assured Produce (Assured Produce, 2008; WRAP, 2011).

Curing of onions	Air flow rate V (m^3/hr·t)	Temperature T (°C)[a]	Curing time (days)	Natural gas (MJ/kg)
1st stage drying	425	28	3	0.287
2nd stage drying	170	25	21	0.528

[a] Temperature of hot air required for drying, assuming the initial temperature of air of 20 °C.

Table 5
Energy consumption in various processing steps per kg of final product.

Processing step/unit	Electricity (MJ/kg)	Heat (MJ/kg)	Steam (kg/kg)	Refrigerant (kg/kg)	Product composition	Reference
Washing, sorting, packing	0.216					(WRAP, 2014)
Slicing/cutting	0.032					(European Commission, 2006)
Peeling	0.013		0.9			(European Commission, 2006)
Blanching	0.031		0.137			(European Commission, 2006)
Freezing	0.648			4.62×10^{-5}		(DEFRA, 2008; European Commission, 2006)
Canning/pickling	0.203	2.58				(Masanet et al., 2008)
Canning tomatoes	0.077		0.8		60% tomatoes, 40% concentrate juice	(European Commission, 2006; Garofalo et al., 2017)
Canning pulses	0.328	2.29			100% tomatoes	(Durlinger et al., 2017)
Tomato concentrate	0.387		2.55		100% tomatoes	(European Commission, 2006)
Tomato ketchup	0.38	1.7			19% tomato paste, 39% water, 30% sugar, 3% salt, 9% vinegar	(Andersson et al., 1998; Mccarthy and Mccarthy, 2009)
Frozen chips	0.864	5.39		6.42×10^{-5}	95% potatoes, 5% oil	(DEFRA, 2008; Ponsioen and Blonk, 2011)
Crisps	0.95	2.34	3.37		73% potatoes, 26% oil, 1.4% salt	(European Commission, 2006; Nilsson et al., 2011; Wu et al., 2012)

processed and frozen vegetables are assumed to be packed in low density polyethylene (LDPE) bags. The weight of the packaging material per kg of vegetable is based on the average value of 39 g/kg from the range of 2–61 g/kg (Gottfridsson, 2013; Milà i Canals et al., 2007; Stoessel et al., 2012; WRAP, 2014). Fresh tomatoes are sold in three packaging types: polypropylene (PP) flow wrap, polyethylene terephthalate (PET) trays and PET punnets (WRAP, 2011). As their share is not available, equal proportions have been assumed (23%), taking the share of loose produce (30.7%) into account. The weight of the punnet packaging has been obtained from Roy et al. (2008), while the weight of PET trays is based on own measurements.

Some vegetables are tightly wrapped, such as fresh cucumber and broccoli, rather than packaged in plastic bags. The amount of wrapping used has been determined through own measurements. Cauliflower, cabbage and squash are generally sold loose; therefore, only cardboard packaging is considered for transportation. Pickled vegetables are packed in glass jars with a steel lid. A number of jars from different manufacturers have been weighed to determine their average weight. The polyethylene (PE) label are also considered. In the case of asparagus, it is assumed that 70% of the preserved asparagus is packaged in glass jars, while the remaining is canned, based on the retail situation in the UK. The weight of cans is based on canned tomatoes (Garofalo et al., 2017).

Potato crisps are packed in bags consisting of an outer (PP) and an inner layer (aluminium); their weights are based on data in Nilsson et al. (2011). Chips packaging material and weight are from Mouron et al. (2016). Ketchup is assumed to be sold in PET bottles.

Tomato paste concentrate is filled in an aluminium tube and sealed with a high density polyethylene (HDPE) lid. The weights for both packaging types are based on own measurements. As mentioned earlier, ketchup is made from tomato paste produced in Mediterranean countries which transported in bulk to the UK and the Netherlands, where it is processed into ketchup. Andersson and Ohlsson report that the tomato paste is transported in aseptic bags, which are placed in steel drums (Andersson and Ohlsson, 1999). Data on the aseptic bags and steel drums have been obtained from Dargan (2011).

Table 6 summarises the different packaging materials along with the packaging weights for fresh and processed vegetables. Waste management of packaging is detailed in section 2.3.10.

2.3.6. Transport

Transportation is considered in each life cycle stage, including ambient and refrigerated trucks. Table 7 lists the distances assumed for road transport. These apply both in the UK and in the country of origin for imported produce.

The transport mode for imported vegetables varies depending on the country of origin. Fresh, chilled and frozen produce are transported refrigerated, while the remaining processed vegetables are shipped at ambient conditions. Within Europe, it is assumed that vegetables are transported by road, with the exception of Greece, for which sea shipping is assumed. Fresh vegetables imported from outside Europe are air-freighted or shipped (Table 8), while all processed vegetables are shipped.

The distances assumed between the UK and the exporting countries are detailed in Table 9 for the different transportation modes. Sea shipping and air-freighting include road transportation to the ports and airports, assuming a generic distance of 360 km (Dargan, 2011). The road and air distances have been obtained from Foodmiles.com (2016), while the sea distances have been calculated based on the nautical miles from Ports.com (2018).

Refrigerated transport is based on non-refrigerated transport in Ecoinvent (2010), modified for the refrigerated transportation by adding a refrigerant and increasing fuel consumption and related emissions by 20%.

Table 6
Packaging used for different vegetable products.

Packaging type	PE[a]	PP[b]	PET[c]	Aluminium	Steel	Glass	Cardboard
	(g/kg_{veg})						
Plastic bag (other than tomato)	39						6
Plastic bag (tomato)	0	3.9					6
Plastic wrap (cucumber)	5						6
Punnet with wrap	3.7		53				115
Plastic tray with wrap	3.9		49.4				60
Can (tomato)	4.3				200		46
Can (other than tomato)[d]	7.2				330		76
Glass jar (tomato)					20	600	46
Glass jar (other than tomato)					50	1240	
Crisp bag		33.9		1.2			36
Chips	4.9						36
Ketchup bottle	4.7		86.2				46
Aluminium tube	4.7			77.5			46
Drum (bulk tomato paste)	0.4		4.2	3	64.2		

[a] PE: polyethylene.
[b] PP: polypropylene.
[c] PET: polyethylene terephthalate.
[d] The amount of packaging is higher compared to tomatoes, due to a higher net weight.

Table 7
Assumed distance in each life cycle stage.

Stage	Distance	Truck type[a], temperature	Reference
Farm to storage	50 km	HGV, ambient	Assumption
To processing	100 km	HGV, ambient	Assumption
To retail	95 km	HGV, refrigerated	(DEFRA, 2008)
To waste facilities	100 km	HGV, ambient	Assumption

[a] HGV: heavy goods vehicle.

2.3.7. Retail

The storage of fresh vegetables in retail stores depends on the type of vegetable. Based on own survey of UK retail stores, it is assumed that fresh asparagus, beans, broccoli, Brussels sprouts, carrots, cauliflower, courgettes, lettuce, peas, spinach and sweetcorn are stored in chilled display cabinets and the rest of the vegetables at ambient conditions. Canned, pickled and dried vegetables are also stored at ambient temperature, along with ketchup, tomato paste and potato crisps. The electricity consumption and refrigerant leakage for the retail stage have been sourced from DEFRA (2008), which provides data for potatoes, frozen peas and frozen chips. For other refrigerated vegetables, data for refrigerated strawberries are assumed (DEFRA, 2008). The refrigeration energy for pre-prepared vegetable products has been estimated based on the data for chilled ready-made meals in DEFRA's report.

2.3.8. Refrigerant leakage

Leakage of refrigerants is considered at processing plants for frozen products, at retailers and during refrigerated transport. For the processing and retail stages, it is assumed that 15% of the refrigerant loads leaks annually, while for transport, the leakage rate is 17.5% (DEFRA, 2008). A commonly used refrigerant R-404A has been assumed in the study, with its constituent components and the global warming potentials given in Table 10.

2.3.9. Household consumption

The energy used for refrigeration and cooking as well as the water to boil vegetables have been considered in the consumption stage. The electricity for refrigeration has been calculated based on the total energy consumption of a fridge, its capacity, storage duration and the specific volume of the product. The last two are shown in Table 11. The mean annually energy used by fridge-freezers of 260 L is 444 kWh (Palmer et al., 2013). It is assumed that on average 40% of the appliance capacity is occupied.

In this study, most fresh vegetables are assumed to be refrigerated before being consumed, based on common practice in the UK. Potatoes, onions and tomatoes are stored refrigerated in some households, with the estimated proportions of 17%, 10% and 50%, respectively (Milà i Canals et al., 2007; WRAP, 2012). All tomatoes are assumed to be stored refrigerated due to the high perishability. Frozen vegetables are kept in freezers for 15 days (Milà i Canals et al., 2007). Preserved vegetables, such as ketchup, cans and pickles are stored at ambient temperatures, along with dried vegetables. Some households may keep opened preserves refrigerated but, due to a lack of data, this is not considered. However, as vegetables in opened cans should be consumed within three days, even if they are refrigerated, the overall impacts may be small relative to those from the rest of the supply chain. In contrast, ketchup has a long shelf life after being opened. Therefore, it is assumed that 50% of the households keep ketchup refrigerated for 60 days. Non-perishable vegetables, such as cabbage and winter squash, are not considered to be refrigerated at home, especially due to the bulky size.

Vegetables are eaten raw, boiled, fried or roasted. The different preparation methods, cooking periods and water volumes are given in Table 12 as average values for the fresh and processed vegetables. In general, canned vegetables are assumed to be heated up on a hob or in microwaves. Most pickles are consumed raw, apart from pickled cabbage, which is also common to be cooked.

2.3.10. Waste management

Waste management options considered in different life cycle stages are summarised in Table 13, following the UK waste management practice. The proportion of waste generated in each stage is collated in Table 14. As shown in the latter, proxy data have been used for some vegetables; where no proxy was suitable, the average value of the share of waste generation of various vegetables has been assumed. The percentage of household waste has been calculated considering the purchased vegetable quantities and the amount thrown away (DEFRA, 2014b; WRAP, 2013). Where data on waste generation were missing, the category of "fresh vegetables and salads" has been used as an average value for the fresh vegetables, as well as the generic category of "processed vegetables" (see Table 14).

2.3.11. Water use and water footprint

Water is used in each life cycle stage, either directly or indirectly. Water is used directly to irrigate crops and to wash, peel, blanch and pasteurise the vegetables. It is also needed for cleaning of processing plants. The consumer also uses water to wash and cook vegetables (see Table 12).

The irrigation water volumes have been obtained Mekonnen and Hoekstra (2010) considering blue water. The washing water used in processing is based on the BAT report (European Commission, 2006) and is listed in Table 15 for different vegetables, along with the water required for the various processing steps of frozen vegetables, such as peeling and blanching. It is assumed that root vegetables, such as carrots and beetroot, have a similar water usage as potatoes. It is also assumed that vegetables grown in greenhouses, such as aubergines, sweet

Table 8
Percentage of fresh vegetables air-freighted and shipped from outside Europe (Marriott, 2005).

Transport mode	Beans	Peas	Asparagus	Peppers	Onions	Brussels sprouts	Aubergines
By air	69.7%	74.9%	74.7%	3.2%	1.3%	7.5%	4.0%
By sea	30.3%	25.1%	25.3%	96.8%	98.7%	92.5%	96.0%

Table 9
Assumed distance travelled for imported vegetables to the UK by road, sea and air, based on Foodmiles.com and Ports.com (Foodmiles.com, 2016; Ports.com, 2018).

Country of origin	Road (km)	Sea (km)	Air (km)	Country of origin	Road (km)
Greece	360	5760	–	Spain	1270
Kenya	360	12,470	6820	Netherlands	360
Morocco	360	3480	2020	Italy	1430
Egypt	360	3690	3510	Portugal	1590
Canada	360	5930	5360	Germany	930
USA	360	8830	5900	France	340
Guatemala	360	12,150	8770	Belgium	320
Zimbabwe	360	15,570	8280	Ukraine	2130
Peru	360	15,360	10,170	Hungary	1450
Israel	360	6750	3610	Poland	1450
South Africa	360	13,040	9020		
Mexico	360	15,200	8930		

Table 10
Components of R-404A and the global warming potentials (IPCC, 2007).

Refrigerant	Contribution (%)	GWP (kg CO_2 eq./kg)
R-134A	4	1430
R-125	44	3500
R-143A	52	4470
R-404A	100	3922

Table 11
Refrigeration period of vegetables and their specific volumes in the household stage.

Vegetable	Refrigeration period (days)	Specific volume (L/kg)	References
Asparagus	3.5	Assumed as green beans	(Fresh Direct, 2018)
Aubergines	4.5	1.7	(Fresh Direct, 2018; Jha and Matsuoka, 2002)
Beans (green)	5	2.4	(Milà i Canals et al., 2007)
Beans (frozen, pulses)	15	Assumed as peas	
Beetroot	10	Assumed as carrots	
Bell peppers	7	1.42	(Bozokalfa and Kilic, 2010; Fresh Direct, 2018)
Broccoli	5	5	(Milà i Canals et al., 2007)
Brussels sprouts	5	2.49	(Machine and Process Design, 2015)
Cabbage	No refrigeration		
Carrots (whole)	10	1.56	(Machine and Process Design, 2015; Milà i Canals et al., 2007)
Carrots (chopped)	5	1.85	(FAO/INFOODS, 2012; Fresh Direct, 2018)
Cauliflower	5	Assumed as broccoli	
Celery	5	Assumed as courgettes	
Courgettes	5	1.04	(Fresh Direct, 2018; Gholami et al., 2012)
Cucumber	7	1.06	(Mousavizadeh and Mashayekhi, 2010)
Lettuce	5	7.1	(Milà i Canals et al., 2007)
Onions	10	1.6	(Milà i Canals et al., 2007)
Onions (cubed, frozen)	15	1.82	(FAO/INFOODS, 2012; Milà i Canals et al., 2007)
Peas (fresh, shelled)	5	1.7	(Milà i Canals et al., 2007)
Potatoes	14	1.3	(Milà i Canals et al., 2007; WRAP, 2012)
Spinach (fresh)	4	12.5	(FAO/INFOODS, 2012; Fresh Direct, 2018)
Spinach (frozen)	15	0.96	(FAO/INFOODS, 2012)
Squash	No refrigeration		
Sweetcorn (on the cob)	2.7	3.7	(FAO/INFOODS, 2012; Fresh Direct, 2018)
Sweetcorn (shelled)	2.7	1.39	(FAO/INFOODS, 2012; Fresh Direct, 2018)
Tomatoes	5	1.04	(Sônia Cachoeira-Stertz et al., 2005)

peppers, cucumber and courgettes, require the same amount of washing water as tomatoes. For the remaining vegetables, an average amount of water required to wash potatoes and tomatoes is assumed. Canned vegetables require 3.6–6 L/kg of water (European Commission, 2006); an average value of 4.75 L/kg is assumed for all canned vegetables due to a lack of specific data. This includes washing and process water. Additionally, brine water for pickled and canned vegetables has also been considered, which varies for the different vegetables between 0.25 and 0.82 L/kg based on UK retail survey for various canned vegetables. Water consumption for frozen vegetables includes peeling, blanching and pasteurising and varies among the vegetables as indicated in Table 15.

Water is also consumed indirectly for energy conversion, production of packaging, refrigerants, pesticides, detergents and transportation fuels as well as for wastewater treatment. The indirect water volumes used in these processes are provided in Table 16. The energy consumption has been sourced from Ecoinvent for most production processes. For the plastic packaging materials, the data are from PlasticsEurope (2016) while the water demand for metal and glass packaging has been sourced from Gerbens-Leenes et al. (2018).

The water footprint has been estimated according to the methodology developed by Pfister et al. (2009a). This considers the volume of blue water, weighted for the water stress index (WSI) of each vegetable-producing country. Table 17 contains the WSI for the UK and the countries from which the UK imports the various vegetables.

Table 12
Average cooking times and assumed proportions of cooking methods used by households.

Vegetable type	Cooking time (min/kg)	Water (L/kg)	Raw	Boiled	Fried	Roasted	Microwaved
Asparagus	11.6	2.2	9%	45%	16%	24%	6%
Aubergines	14.8	1	0%	20%	30%	30%	0%
Beans	9.3	1	0%	32%	21%	4%	44%
Beetroot	22.4	3.4	3%	68%	0%	29%	0%
Bell peppers	13.5	0.9	18%	18%	46%	18%	0%
Broccoli	12	2.6	0%	52%	26%	16%	6%
Brussels sprouts	11.9	2.8	0%	56%	20%	20%	5%
Cabbage	11	3.5	2%	71%	14%	10%	2%
Carrots	17.5	1.4	17%	30%	21%	28%	4%
Cauliflower	11.2	3.7	0%	73%	14%	12%	2%
Celery	11	1	0%	20%	40%	40%	0%
Courgettes	11	1	0%	20%	40%	40%	0%
Cucumber	0	0	100%	0%	0%	0%	0%
Lettuce	0	0	100%	0%	0%	0%	0%
Onions	12.8	0.1	11%	10%	59%	20%	0%
Peas	16.6	2.7	0%	48%	20%	0%	32%
Potatoes	23.8	1.9	0%	35%	0%	41%	15%
Spinach	9.4	0.4	4%	37%	37%	0%	22%
Squash	35	2.5	0%	50%	0%	50%	0%
Sweetcorn	11	1	11%	28%	25%	14%	22%
Tomatoes	3.9	0.2	66%	17%	17%	0%	0%

2.3.12. Assumptions and limitations

With limited data availability, a number of assumptions had to be made for different products. These have been discussed at length in the previous sections but are summarised here to provide an overview of the limitations of the study:

- Agriculture: In some cases, data were not available for the specific producing countries and proxy data had to be used instead.
- Storage: Post-harvest treatment requires the use of pesticides to extend the life span of vegetables, in particular over long storage periods. The lack of data on specific pesticides necessiated the use of average data.
- Processing: For some processing plants, data are based on European

Table 13
Waste management in the UK (WRAP, 2016).

Waste management	Food waste			Packaging waste
	Processing	Retail	Household	Household
Recycling (anaerobic digestion/compost)	33%	50%	20%	
Energy recovery	66%	50%	20%	40%
Disposal (landfill, sewer)	1%	0%	61%	60%
Cans (landfill/recycling)				25%/75%
Glass (landfill/recycling)				50%/50%

Table 14
Waste generation in different life cycle stages based on (DEFRA, 2014a; Gottfridsson, 2013; WRAP, 2011, 2013).

	Farm	Grading	Storage	Packaging/processing	Retail	Household		Proxy
						Fresh	Processed	
Asparagus	5.9%	9.4%	3%	4.1%	2.4%	34%	7%	Fresh vegetables and salad category
Beetroot	20%			35% (fresh), 23% (processed)		As carrots		
Beans (overall)	5.9%	9.4%	3%	4.1%	2.4%	11%	3%	
Bell peppers	5.9%	9.4%	3%	4.1%	2.4%	31%	5%	
Broccoli	10%	3%	–	–	2.3%	45%	25%	
Brussels sprouts	10%	3%	–	–	2.3%	As cabbage		
Cabbage	10%	3%	–	–	2.3%	45%	13%	
Carrots	20%			35% (fresh), 23% (processed)		42%	11%	
Cauliflower	10%	3%	–	–	2.3%	27%	29%	
Celery	5.9%	9.4%	3%	4.1%	2.4%	34%		
Courgettes & aubergines	5.9%	9.4%	3%	4.1%	2.4%	34%		Fresh vegetables and salad category
Cucumber	5%	7%		4%	2.8%	28%	5%	
Lettuce	7.5%		1.3%	1%	2%	44%		
Onion	4%	14.5%	6.5%	2.5%	0.8%	41%	21%	
Peas (overall)	5.9%	9.4%	3%	4.1%	2.4%	47%	8%	
Potatoes	1.5%	8%	4%	22.5%	2.3%	46%	13% (chips), 9% (crisps)	Processed potatoes; savoury snacks (70% crisps)
Spinach	5.9%	9.4%	3%	4.1%	2.4%	34%	7%	Fresh vegetables and salad category
Squash	5.9%	9.4%	3%	4.1%	2.4%	35%		
Sweetcorn	5.9%	9.4%	3%	4.1%	2.4%	35%	7%	Processed sweetcorn: "processed vegetables"
Tomatoes	5%	7%		4%	2.8%	17%	9% (processed), 10% (ketchup)	Ketchup: sauces

average values, including the plants outside Europe.

- Retail: Refrigerated storage varies among the retailers but no data are available on common practices and storage periods for various vegetables. Therefore, these have been assumed based on own survey.
- Household consumption: No data were available on household storage and cooking behaviour and so recommended practices have been assumed.
- Waste: The amounts of vegetable waste across the supply chains were not available for all products, necessitating the use of data for other vegetables or average waste percentages. Moreover, the share of waste and its management practices were not known for imported vegetables and the UK data have been used instead.

Table 15
Washing and process (blue) water used for different vegetables (European Commission, 2006).

Vegetables	Washing water (L/kg)	Water demand for frozen vegetables (L/kg)
Asparagus	3.85	As courgettes and aubergines
Aubergines	2	2.6
Beans	3.85	3
Beetroot	5.7	–
Brussels sprouts	3.85	As cabbage
Cabbage	3.85	2.6
Carrots & turnips	5.7	3.8
Cauliflower & broccoli	3.85	3
Celery	5.7	2.6
Courgettes	2	2.6
Cucumber	2	–
Lettuce	3.85	–
Onion	3.85	2.6
Peas	3.85	3
Potatoes	5.7	3.8
Spinach	3.85	5.1
Squash	3.85	–
Sweet peppers	2	–
Sweetcorn	3.85	As peas
Tomatoes	2	–

2.4. Impact assessment

The life cycle environmental impacts have been estimated using GaBi V6 software (PE International, 2014), according to the ReCiPe method, version 1.08 (Goedkoop et al., 2013). To ensure a comprehensive analysis and avoid shifting ('leakage') of environmental impacts, all 17 impact categories included in the ReCiPe are considered as follows: global warming (GWP), agricultural and urban land use (ALO, ULO), land use change (NLT), eutrophication of fresh and marine waters (FE, ME), human toxicity (HT) and eco-toxicity of fresh and marine waters as well as soil (FET, MET, TET), fossil and metal depletion (FD, MD), ozone depletion (OD), photochemical oxidants formation (POF), formation of particulate matter (PMF), terrestrial acidification (TA) and ionising radiation (IR). In addition, primary energy demand and water footprint have been estimated using GaBi (PE International, 2014) and Pfister et al.'s method (Pfister et al., 2009b), respectively.

3. Results and discussion

The results are first discussed for the environmental impacts per kg of vegetables, followed by the estimates of the total annual impacts at the sectoral level.

Table 16
Indirect blue and green water demand (Ecoinvent, 2015; Gerbens-Leenes et al., 2018; PlasticsEurope, 2016).

Water usage	Unit	Blue	Green	Water usage	Unit	Blue
Heat, natural gas	L/MJ	0.2	–	Road - refrigerated	L/t·km	0.234
Electricity – RoW[a]	L/MJ	1.9	–	Sea - refrigerated	L/t·km	0.017
Electricity – UK	L/MJ	0.8	–	Air - refrigerated	L/t·km	1.378
PP, PET	L/kg	4.8	–	Pesticide	L/kg	15.59
LDPE	L/kg	2.9	–	Sodium hydroxide	L/kg	11.38
Paper	L/kg	0.8	5.4	Hydrochloric acid	L/kg	2.26
Aluminium	L/kg	42	–	Sodium hypochlorite	L/kg	0.518
Steel	L/kg	11.83	–	Refrigerant	L/kg	11.61
Glass	L/kg	5.89	–	Wastewater treatment	L/m^3	4.59

[a] RoW: Rest of the world - all regions except the UK.

Table 17
Average water stress indices (WSI) for the UK and the countries from which the UK imports vegetables (Pfister et al., 2009a).

Country of origin	WSI [m^3/m^3]	Country of origin	WSI [m^3/m^3]	Country of origin	WSI [m^3/m^3]	Country of origin	WSI [m^3/m^3]
Belgium	0.715	Guatemala	0.0123	Morocco	0.844	Spain	0.71469
Canada	0.102	Hungary	0.095	Netherlands	0.3056	Ukraine	0.2998
Egypt	0.9766	Italy	0.2726	Peru	0.71588	UK	0.395
France	0.1809	Israel	0.9959	Poland	0.0699	USA	0.499
Germany	0.12	Kenya	0.0208	Portugal	0.573	Zimbabwe	0.1917
Greece	0.7109	Mexico	0.756	South Africa	0.6865		

3.1. Impacts at the product level

The impacts discussed in this section are based on the functional unit of 1 kg of vegetables consumed. They represent the overall impacts of each vegetable type estimated by taking into account the market share of fresh and processed products, produced both domestically and imported (based on the data in Table 1). The impacts of individual vegetables and their products can be found in the Supporting information (SI). Primary energy demand and the water footprint are discussed first, followed by the impacts estimated according to the ReCiPe method.

3.1.1. Primary energy demand (PED)

The total primary energy demand (PED) is depicted in Fig. 2, along with the relative contribution of different life cycle stages. As can be seen, the PED ranges from nearly 12 MJ/kg for celery, courgettes and cabbage products to 64.7 MJ/kg for asparagus. As can be seen in Fig. S1, UK-produced vegetables have generally lower impacts than the imported equivalents. The exceptions to this are aubergines, cucumber, peppers and tomatoes which in the UK are grown in heated greenhouses while the imported produce is either grown in open fields or in unheated greenhouses. Therefore, in these cases, even transporting the produce over long distances consumes less primary energy than cultivating them in heated greenhouses, provided they are sourced from Europe and transported by road.

The results also show that processed products have higher PED than the fresh, which is to be expected (Figs. S2–S11). An exception to this trend is the air-freighted fresh produce, which can have a higher overall impact than processed products. This is particularly the case for fresh air-freighted asparagus. As indicated in Fig. 2, transport consumes 54% of the total PED of asparagus, although the air-freighted fresh produce makes up only a third of all asparagus consumed in the UK. Similarly, transport contributes 42% to the total PED of beans, although only 6% of the beans are air-freighted. Additionally, almost all beans consumed in the UK are imported from outside of Europe, travelling long distances. The transportation stage also contributes notably to the PED of courgettes and celery (35% and 30%, respectively), since the majority are sourced from abroad. For the remaining vegetables, transport contributes 10%–21% of the total, except for Brussels sprouts, carrots, lettuce and potatoes (5%–8% of total PED).

The farm production is the main hotspot for all vegetables cultivated in heated greenhouses, particularly aubergines, cucumber, peppers and tomatoes. Aubergines have the highest farm-level PED (33.3 MJ/kg) as they need higher temperatures (25-28 °C) to grow. Although tomatoes require similar temperatures, most tomatoes are imported from Italy and Spain, where they are grown in fields or unheated greenhouses. By contrast, most aubergines are produced in heated greenhouses in the Netherlands.

The storage stage is a significant contributor (21%–34%) for all winter vegetables (carrots, onions, beetroot, potatoes and cabbage), which are stored for several months at low temperatures. Carrots and beetroot have the highest PED for storage (6.3 MJ/kg) due to the low storage temperature (0 °C) and long storage time (seven months). Potatoes are stored even longer (eight months), but at higher temperatures (up to

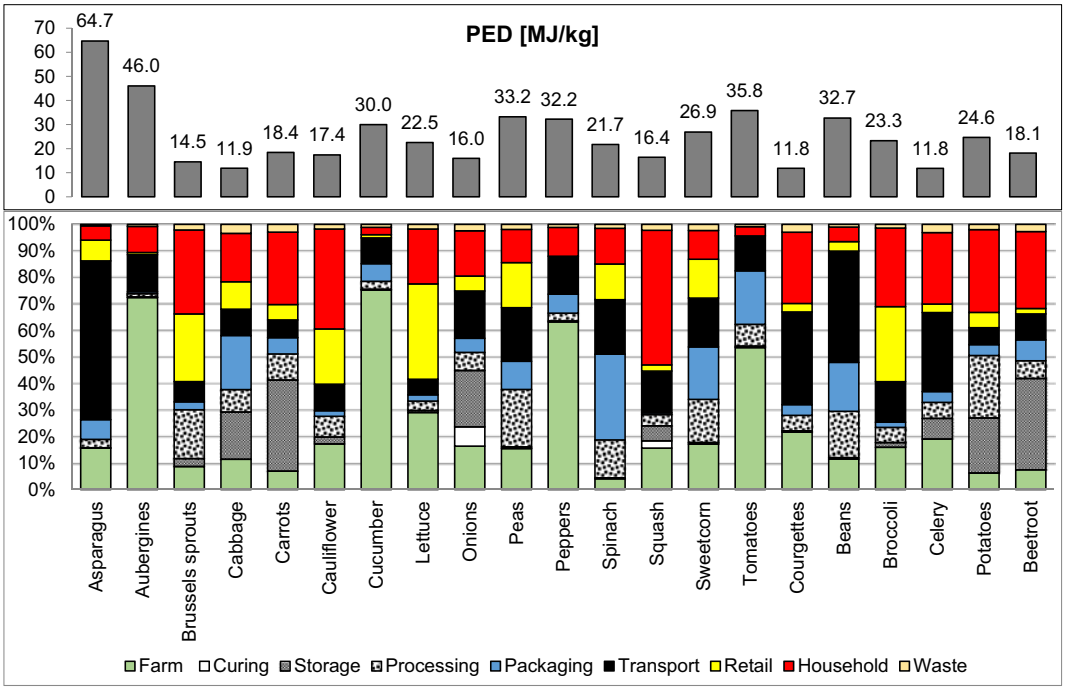


Fig. 2. Primary energy demand (PED) and contribution of different life cycle stages.

5 °C). The curing process contributes 7% to the total PED of onions and 3% of winter squash.

For the vegetables which require further processing, such as freezing or conversion into other products (e.g. crisps and chips), processing is a significant energy consumer. This is especially notable in the case of peas, potatoes and beans. Peas have the highest PED (7.2 MJ/kg) in the processing stage due to the high proportion of frozen peas (54%), followed by potatoes (5.8 MJ/kg) due to crisps and chips. The production of the latter two as well as tomato paste is the most energy intensive stage and as a result these products have around three times higher PED than their fresh counterparts. For processing of baked beans, the PED is partly due to the use of tomato paste and partly due to the heat used in baking.

The packaging stage contributes significantly to the PED of canned and pickled vegetables. Since 60% of spinach is sold in cans, packaging is its main hotspot, accounting for 32% of the total energy demand. Packaging is also important for tomatoes and sweetcorn due to a high share of packaged products. For sweetcorn, the PED is mainly related to cans, as 45% of sweetcorn is canned. For tomatoes, PED is largely due to PET used for ketchups bottles, punnets and trays for fresh tomatoes, and to some extent, due to the use of glass jars and cans. Similarly, cabbage packaging accounts for 20% of its total PED as 9% is pickled cabbage packaged in glass jars.

Refrigerated retail is a significant contributor for lettuce, broccoli, Brussels sprouts, cauliflower, peas, sweetcorn and spinach, accounting for 13%–33% of the total PED.

Household consumption contributes significantly to the PED of most vegetables (10%–51%), except for asparagus, beans, cucumber and tomatoes. The main energy consumers are refrigeration and cooking. Oven baking is the most energy intensive cooking option and so vegetables that are typically baked, such as squash and potatoes, have higher PED. Some vegetables, such as dried beans and other pulses, require longer cooking times and hence consume higher energy. Canned or bottled vegetables and those eaten raw have low PED at the household level as they do not require refrigeration or cooking; these include asparagus, tomato and cucumber.

The disposal stage has the lowest energy demand across the vegetables, contributing 1%–3% to the total PED.

3.1.2. Water footprint (WF)

Unlike PED, the WF of UK-produced vegetables is lower than that of imported produce (Fig. S12) as a large share of the imports is from water-stressed countries, in particular Spain. The greatest difference between the UK and imported vegetables is found for the WF of celery (32-fold), followed by aubergines and spinach. Carrots, cauliflower, courgettes and broccoli grown in the UK have a nine-fold lower impact than the vegetables from overseas. All fresh produce has a lower WF than their processed products (Figs. S13–19).

As indicated in Fig. 3, the volume of blue water and the resulting WF varies widely among the vegetables. Asparagus has the highest WF (525 L eq./kg) due to two reasons: i) all imported asparagus originates from water-stressed countries, such as Peru, Spain and Mexico; and ii) the blue water consumption for irrigation in these countries is immense due to the warm climate. At the lowest end of the range, peppers require only 8.5 L/kg of blue water and have the WF of 4 L eq./kg. The WF of the remaining vegetables ranges from 7 to 56 L eq./kg.

After asparagus, beans have the second highest WF among the assessed vegetables, estimated at 65 L eq./kg. Farm production causes 91% of the impact, followed by their processing (5%). The WF of imported fresh green beans is 3.4 times higher compared to the domestic green beans. Although the majority is sourced from Kenya, which is characterised as water abundant, a quarter of fresh beans are imported from Egypt, which is highly water-stressed. With respect to pulses, UK fava beans have a 15 times lower WF compared to the imported products, such as kidney beans or chickpeas. Among the processed beans, pulses have the highest WF (231 L eq./kg) and frozen and canned green beans the lowest (14 L eq./kg).

As can be seen in Fig. 3, farm production is the main contributor to the WF for most vegetables, accounting for 74%–98% of the total. This is due to the irrigation water, specifically in warmer countries overseas. For carrots and peppers, processing requires more water than their cultivation, largely due to the washing and the water embodied in the life cycle of energy. Water consumption during processing of cabbage, potatoes and beetroot is also significant, contributing around 20% to the total WF. At the household level, the highest consumption of water is found for cabbage preparation (23%) due to the boiling water and energy consumption. For the other vegetables, the contribution of household preparation is below 10%.

3.1.3. Global warming potential (GWP)

The GWP ranges between 0.8 and 0.9 kg CO_2 eq./kg for celery, courgettes and cabbage to 5.3 kg CO_2 eq./kg for asparagus (Fig. 4). Most root vegetables (carrots, onions and beetroot), winter squash and brassicas (Brussels sprouts and cauliflower) have a relatively low GWP of 1.0–1.3 kg CO_2 eq./kg. For a detailed breakdown of GWP of fresh and processed vegetables produced domestically and imported, see Figs. S20–S61 in the SI.

For asparagus, transportation is the largest contributor (55%) due to two reasons: 74% of asparagus consumed in the UK is imported mainly from Peru; and three-quarters of the imported asparagus is air-freighted. Compared to fresh asparagus grown in the UK, the GWP is nearly five times greater for imported fresh asparagus (Figs. S20 and S21).

Transport is also a major source of the GWP of beans (43%) for similar reasons as for asparagus. Nearly 70% of fresh beans are air-freighted from Kenya, with the GWP of 6 kg CO_2 eq./kg, more than five times the impact of the beans grown in the UK (Fig. S24 and S25). Due to the transportation, imported fresh beans have the highest impact of all bean products, followed by imported baked beans with 2.5 kg CO_2 eq./kg.

Packaging and farm production contribute 16% each to the GWP, followed by the processing stage with 13%. The packaging impact is mainly due to the cans, since 80% of the beans are sold canned. Baked beans are also the highest contributor to the processing stage, mainly due to the heat required for canning as well as the tomato concentrate for the sauce, accounting for 39% and 48%, respectively.

Fig. 4 shows that farm production is the main hotspot for aubergines, cucumber, tomatoes and peppers, all of which are cultivated in greenhouses in the UK and other countries with a similar climate, such as the Netherlands. Domestic fresh tomatoes have an order of magnitude higher GWP than the imported (Figs. S60 and S61). This is despite 42% of imports being from the Netherlands (Table 1) where tomatoes are also grown in greenhouses. However, the latter use combined heat and power (CHP), while in the UK only 25% of the energy is supplied by CHP. Also, Dutch production has a 14% higher yield than the average in the UK (Ecoinvent, 2016). Furthermore, the impact of tomatoes cultivated in unheated greenhouses in Spain and in field in Italy is 30 and 78 times lower, respectively, than that in the UK. Packaging and transport are also the significant contributors to the GWP of tomato products, contributing 17% and 13%, respectively. The packaging impact is associated with the use of glass bottles for processed tomatoes, PET bottles for ketchup, steel cans for canned tomatoes and aluminium tubes for tomato paste. With respect to the processed tomato products, tomato paste has the highest impact (4.8 kg CO_2 eq./kg) and ketchup has the lowest (1.5 kg CO_2 eq./kg). The impact of processed products is directly related to the quantity of tomatoes used to make them; e.g. 6 kg of fresh tomatoes are required to produce 1 kg of paste and approximately 2 kg are used in all other products. Interestingly, fresh tomatoes have the higher impact than canned tomatoes. This is due to the high proportion of fresh tomatoes grown in greenhouses, while canned tomatoes are imported from Italy and Spain.

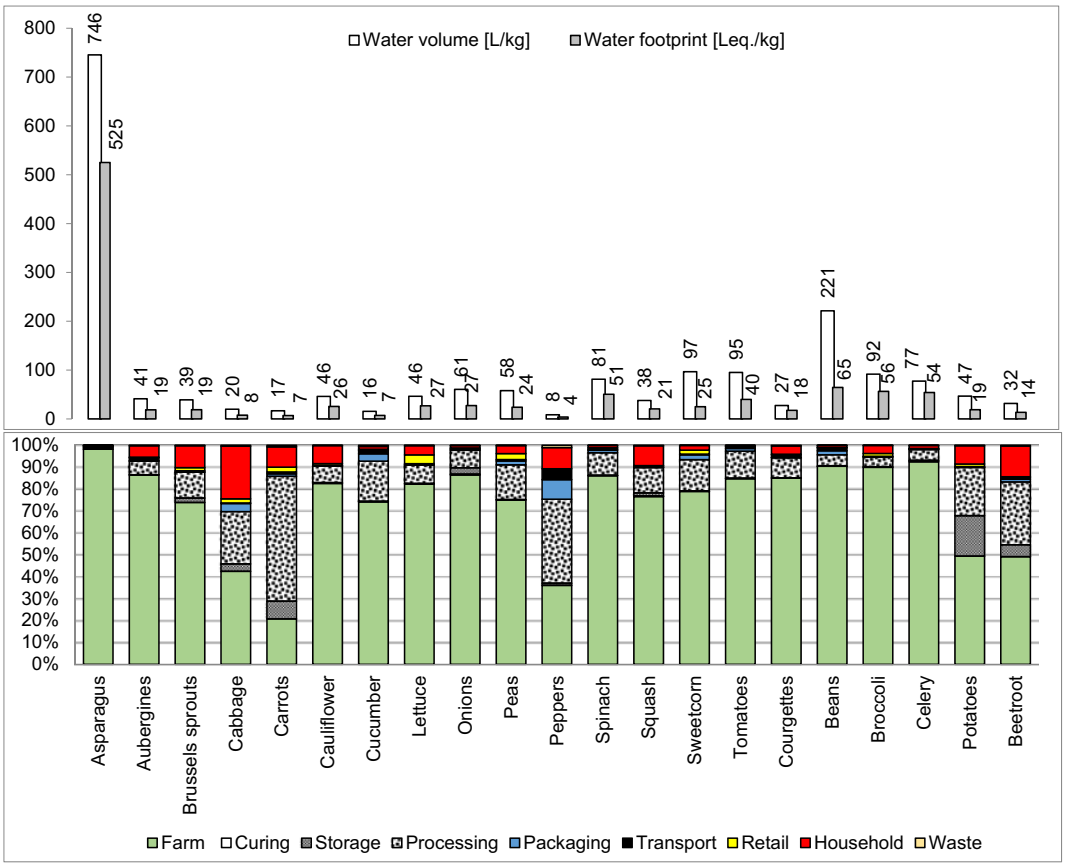


Fig. 3. Blue water consumption and the water footprint of vegetables with contribution of different life cycle stages to the total water footprint.

The GWP of peas is estimated at 2.7 kg CO_2 eq./kg, with farm production, transport and processing contributing around a fifth each, followed by the retail with 16%. Three quarters of fresh imported peas are air-freighted from Latin America and Africa. The impact from processing is largely caused by frozen peas, which account for 54% of the UK market. The GWP from retailing is due to the refrigerated storage of frozen and chilled peas. In terms of imports, the GWP of Spanish peas at farm is five times higher than the GWP of peas in Northern countries because they are irrigated 25 times as much, which requires energy. It is also interesting to note that dry imported peas have a lower GWP

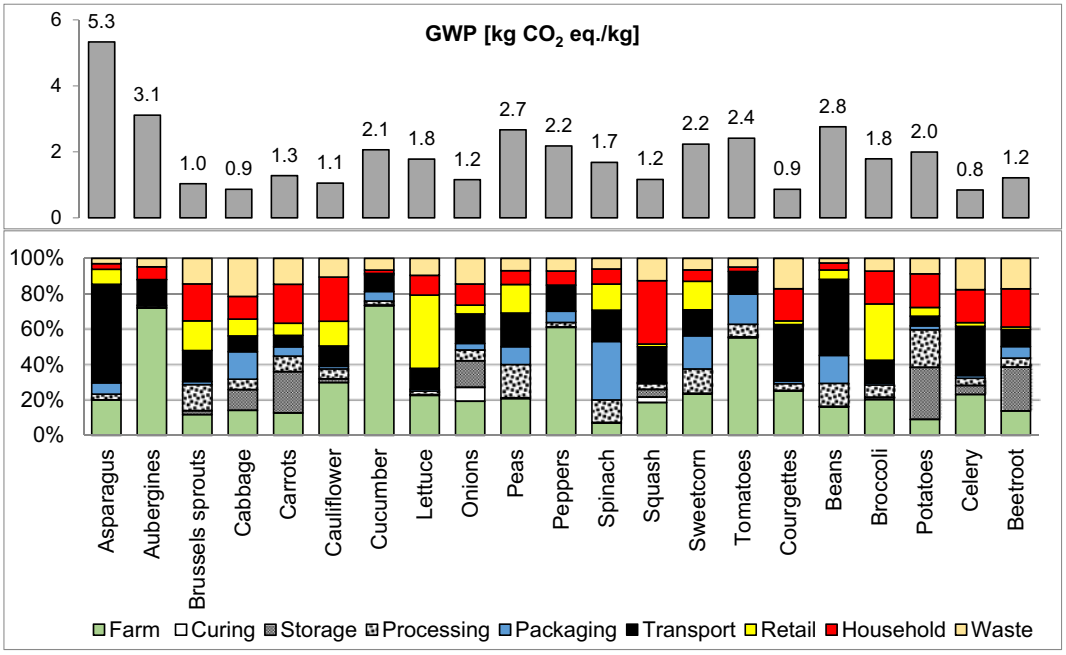


Fig. 4. Global warming potential (GWP) and contribution of different life cycle stages.

than the fresh (Fig. S49) as the latter are air-freighted and the former shipped by sea or transported by road. A similar trend can be noticed for most other impacts.

Sweetcorn has a GWP of 2.2 kg CO_2 eq./kg, the same as peppers. However, while farm production is the main hotspot for the peppers, contributing 60%, for sweetcorn it causes only 23% of the impact, followed by packaging, retail, transport and processing with 14%–19% each. The impact from packaging is largely caused by cans, since 45% of the sweetcorn is sold canned. The rest is frozen and chilled sweetcorn, contributing to the noticeable impact at the retailer. With respect to transportation, road transport within Europe is the main hotspot, since 77% of sweetcorn is imported. The impact from processing is due to the energy intensive processes for freezing and canning, accounting for 60% of the sweetcorn market. With respect to the different products, frozen, canned and pre-prepared sweetcorn have a similar impact. For the frozen product, this is largely due to the processing and retail, for pre-prepared due to the storage at retailer and for the canned due to packaging. Overall, the impact of processed sweetcorn is 60% higher than that of fresh produce (Figs. S58 and S59).

Potatoes and their products have a GWP similar to sweetcorn and peppers (2 kg CO_2 eq./kg). Storage is the greatest contributor (29%), followed by processing and household consumption with around 20% each. As mentioned earlier, half of the fresh potatoes are treated with chlorpropham (CIPC) during storage to inhibit sprout development. Applying CIPC increases the GWP by 2.5 times, compared to cold storage without it. Since processed potatoes (chips and crisps) are treated with a higher concentration of this herbicide and 2-3 kg of potatoes are required to produce 1 kg of processed products, the storage-related impact is higher for the latter compared to the fresh produce by a factor of 4–5 (Figs. S52 and S53). Processed potato products are also a dominant contributor to the GWP in the processing stage, causing around 50 times higher impact than fresh potatoes. The impact at the household stage is mainly due to oven roasting of fresh potatoes and chips. Crisps have the highest impact among the potato products, although the retail and consumption stages generate no impact. This is largely due to the storage and processing stages, proportional to the amount of fresh potatoes being processed per kg of crisps. In the processing stage, vegetable oil contributes significantly, accounting for 26% of the final product.

Storage is also the greatest contributor for carrots and beetroot due to the storage in cold temperatures for up to seven months. Household cooking contributes significantly to the GWP of these two vegetables, since a third of fresh and frozen carrots and beetroot are prepared in ovens, which are twice as energy intensive as boiling on the hob. Heating up canned carrots in microwaves has 3.5–13.5 times lower impact than boiling, frying and roasting. Apart from storage and cooking, disposal of waste has a notable contribution, largely due to the fresh vegetables as 42% of the fresh carrots and beetroot become waste in the household stage (WRAP, 2013). With respect to the different carrot products, frozen carrots have double the impact of fresh carrots, mainly due to the energy required for freezing, retail and cooking.

Onions have a GWP similar to carrots (1.2 kg CO_2 eq./kg). Farm production has the highest impact, followed by transportation, storage, disposal and household cooking, ranging between 12%–19%. The impact from transport is due to the high proportion (54%) of onions being imported, including by air and sea. Storage and waste disposal contribute around 14% each because of chilled storage over five months and the large quantities of wasted onions (40%), respectively. Curing accounts for 8% of the total and is higher than the impacts of processing, packaging and retail. Pickled onions have the highest impact, 2.3 times higher than fresh onions. This is largely due to the glass packaging, which accounts for 60% of the impact. Fresh onions have the lowest GWP, where transportation is the main hotspot for the imported produce and farm production for domestically grown onions.

The lowest GWP is estimated for celery, with transport accounting for a third, followed by farm production, household and disposal. These are respectively due to the large proportion of imported produce (60%), fertiliser application, cooking and high post-consumer waste (34%). Courgettes and cabbage also have a relatively low GWP. For courgettes, the highest impact is caused by transportation, while for cabbage the main hotspot is the disposal stage. Packaging is the second highest contributor for cabbage, mainly because of the glass packaging used for pickled products. For that reason, the latter has the highest impact, five times greater than the fresh produce, with the packaging causing 57% of the total GWP of pickled cabbage. For fresh cabbage, the disposal stage is the most significant, whereas for processed products, it is the retail stage (52%).

3.1.4. Land use

3.1.4.1. Agricultural land occupation (ALO). As indicated in Fig. 5 (and Figs. S20, S21, S48 and S49) asparagus and peas require the greatest area of agricultural land (4.1 and 3.3 m^2a/kg, respectively), followed by potatoes and beans (1 and 1.7 m^2a/kg). For the remaining vegetables, the land occupation is much smaller (0.1–0.6 m^2a/kg). Farm production accounts for more than 60% for most vegetables, apart from cucumber and spinach. For asparagus, farm production occupies 97% of the land due to the cropping cycle of 12 months. For cucumber and spinach, packaging has the highest ALO, contributing 46% and 63%, respectively. This is due to the cardboard packaging used for spinach and glass and cardboard packaging used for cucumber. For instance, pickled cucumber has an eight times higher ALO than fresh cucumber (Figs. S42 and S43), mainly due to the packaging. Furthermore, potato processing contributes 29% to the ALO of potato products, which is related to the use of rapeseed oil for chips and crisps.

3.1.4.2. Natural land transformation (NLT). For the majority of vegetables, the NLT ranges from 1.3 cm^2/kg (cabbage) to 6.6 cm^2/kg (beans); see Fig. 6. Asparagus again has the highest impact, estimated at 16.4 cm^2/kg, largely due to transportation (81%). This in turn is related to the land transformation to produce aviation fuel in refineries. For this reason, the NLT of domestically grown fresh asparagus is 17.5 times lower compared to the imported counterpart (Figs. S20 and S21). Similarly, transportation causes 30%–66% of NLT for the other air-freighted vegetables (Brussels sprouts, beans, aubergines, onions, peas and peppers). It also contributes significantly to the impact of lettuce, spinach, squash, sweetcorn, courgettes and broccoli (30%–54%) due to the large share of these vegetables being imported (54%–81%).

Farm production is the hotspot for aubergines (58%), cucumber (67%), peppers (50%) and tomatoes (45%) due to the energy consumption for greenhouses, with the production of natural gas being the predominant cause of the NLT. The consumption stage is important for NLT of carrots (29%), cauliflower (30%), squash (35%), potatoes (24%) and beetroot (26%) due to the energy consumed for cooking. Storage has a high impact for potatoes, carrots and beetroots accounting 29%–34%. Retail is significant for lettuce (26%) and broccoli (21%), again due to energy consumption.

3.1.4.3. Urban land occupation (ULO). ULO varies from 59.9 $cm^2 \cdot$a/kg for Brussels sprouts to 285.6 $cm^2 \cdot$a/kg for asparagus (Fig. 7). Farm production is the main contributor for most vegetables, accounting for 23%–63%. For cabbage and spinach, packaging is the main hotspot, whereas for lettuce, courgettes and celery, the highest land occupation is related to transport. Packaging is also significant for pickled and canned vegetables (11%–26%). The retail stage contributes notably to the ULO of lettuce (21%) and broccoli (16%). Storage occupies significant urban land for vegetables requiring long storage, such as carrots, onions, cabbage, beetroot and potatoes, contributing 7%–22% to the total. The household stage is responsible for 12%–22% of ULO of Brussels sprouts, carrots, cabbage, lettuce, squash, broccoli, potatoes and beetroot. In the case of potatoes, the contribution of farm production, storage and processing stage is split evenly at around 20%.

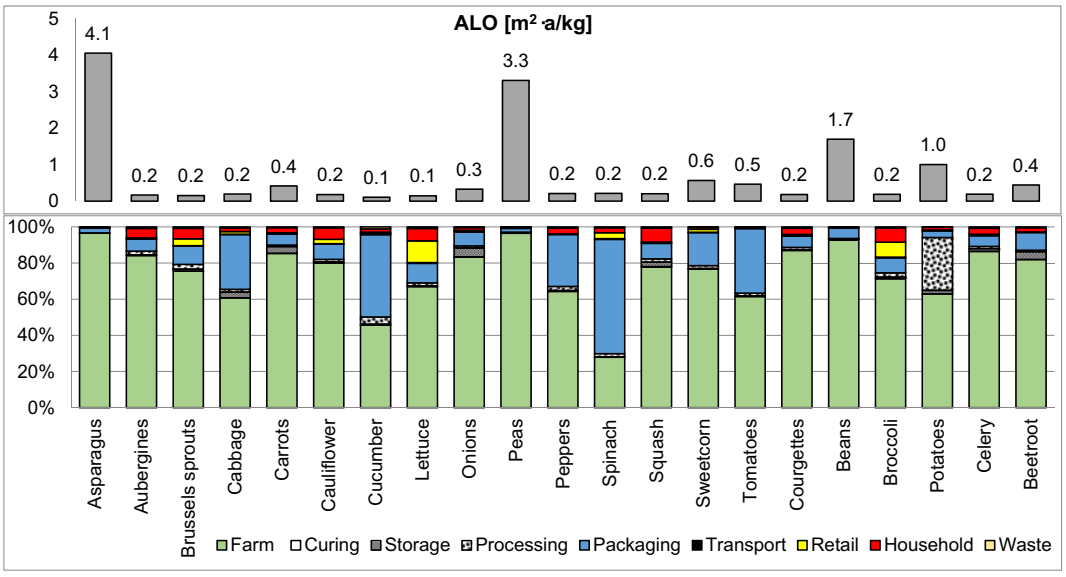


Fig. 5. Agricultural land occupation (ALO) and contribution of different life cycle stages.

3.1.5. Fossil depletion (FD)

Asparagus again has the highest impact, estimated at 1.4 kg oil eq./kg (Fig. 8). This is followed by aubergines, tomatoes and beans (0.69–0.95 kg oil eq./kg). The next highest FD is found for sweetcorn, potatoes, peas, cucumbers and bell peppers, ranging between 0.52 and 0.64 kg oil eq./kg. The rest of the vegetables have an impact of 0.2–0.4 kg oil eq./kg.

Transport is the highest contributor to FD, accounting for 65% of the total for asparagus, mainly due to the air-freighted fresh produce. The contribution of transport is also high for the beans (45%), also due to air-freighting. Farm production causes 56%–78% of the total for aubergines, cucumber, bell peppers and tomatoes due to the use of natural gas in greenhouses. Processing is significant for peas, beans, potatoes and sweetcorn, accounting for 18%–22%. Freezing is the main contributor to the processing stage for peas as more than half of the peas are sold frozen. Baked beans are responsible for the majority of FD in the processing stage of beans since they represent nearly 70% of the beans sector. For potatoes, storage is responsible for 37% of the total impact, largely associated with the herbicide production (CIPC).

3.1.6. Eco-toxicity

3.1.6.1. Freshwater eco-toxicity (FET). Aubergines have the highest (230 g 1,4-DB eq./kg) and Brussels sprouts the lowest FET (24 g 1,4-dichlorobenzene (DB) eq./kg). Farm production, disposal and packaging are the predominant contributors to this impact (Fig. 9). For aubergines and peppers, electricity consumption in greenhouses is the main cause of the impact due to the electricity from coal. Since the electricity consumption for the cucumber production in greenhouses is significantly lower than for aubergines, the FET is lower by a factor of 2.5. In the case of beetroot and carrots, heavy metals associated with the production and application of pesticides and fertilisers as well as manure application are the main sources of impact. For asparagus from Peru, irrigation contributes 84% of the impact during farming. The disposal

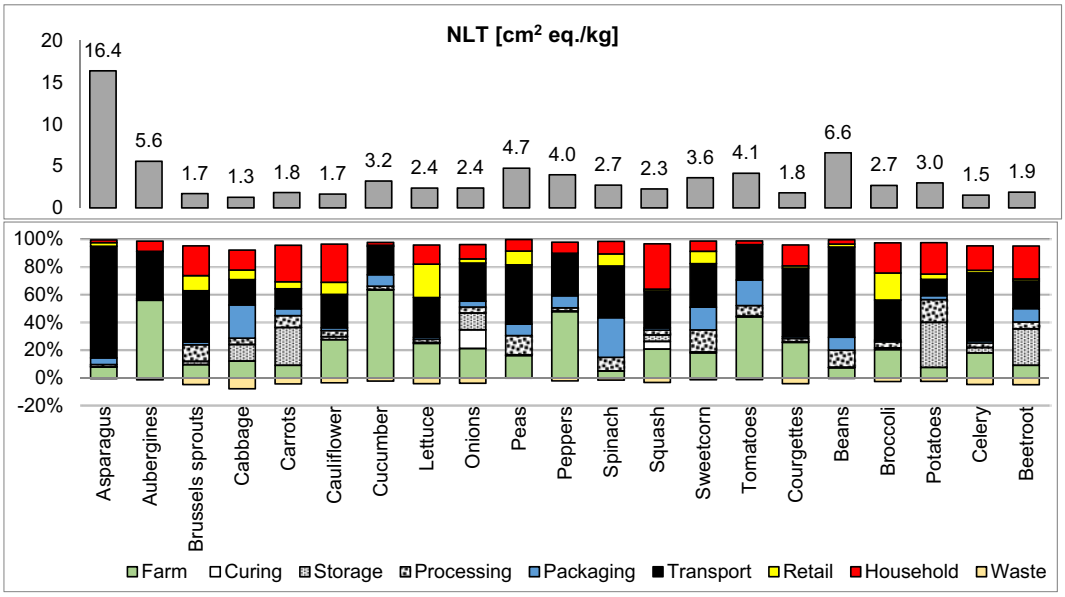


Fig. 6. Natural land transformation (NLT) and contribution of different life cycle stages.

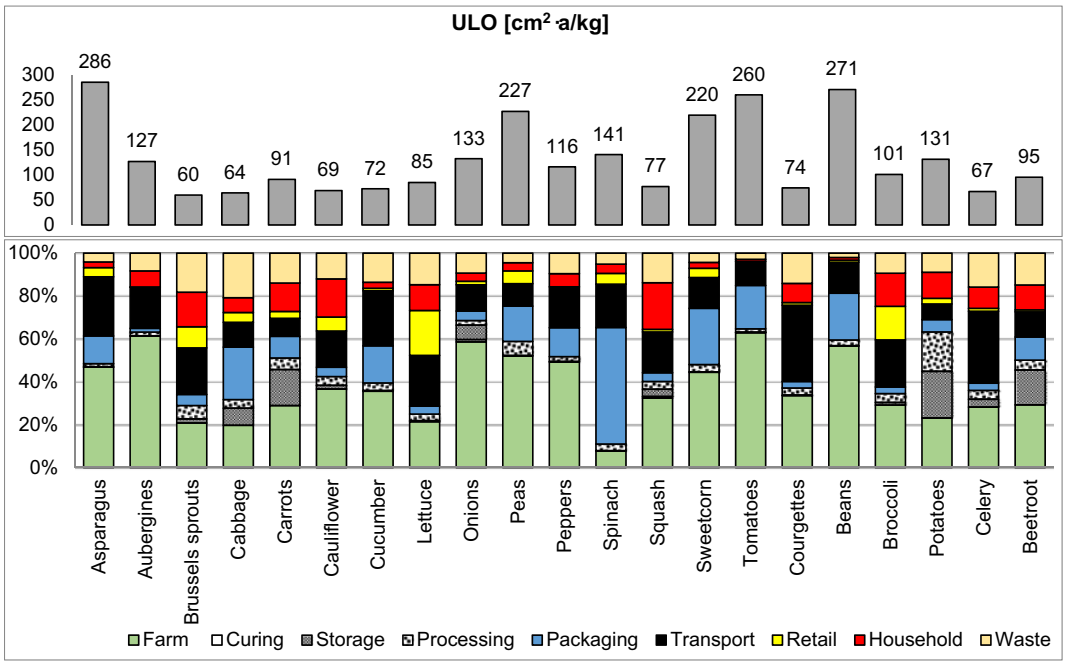


Fig. 7. Urban land occupation (ULO) and contribution of different life cycle stages.

stage is a notable contributor for some vegetables, including Brussels sprouts (42%) and cabbage (38%) due to the household waste and wastewater treatment.

Potatoes have the highest impact in the storage and processing stages among all the vegetables. The FET of crisps is the highest, being 33 times higher than that of fresh potatoes. The vegetable oil in crisps accounts for 91% of the impact. Processing has also a noticeable impact for broccoli, spinach and sweetcorn, related to the energy used for freezing.

Packaging accounts 40% of the FET of spinach due to the high proportion of canned product. For beans and cabbage, packaging is responsible for around a quarter of the impact.

3.1.6.2. Marine eco-toxicity (MET). As can be seen in Fig. 10, this impact ranges from 18.5 to 183.8 g 1,4-DB eq./kg for Brussels sprouts and aubergines, respectively. The peppers also have a relatively high impact (180.1 g/kg). Farm production is the predominant contributor, accounting for around 90% for aubergines and peppers due to the greenhouse

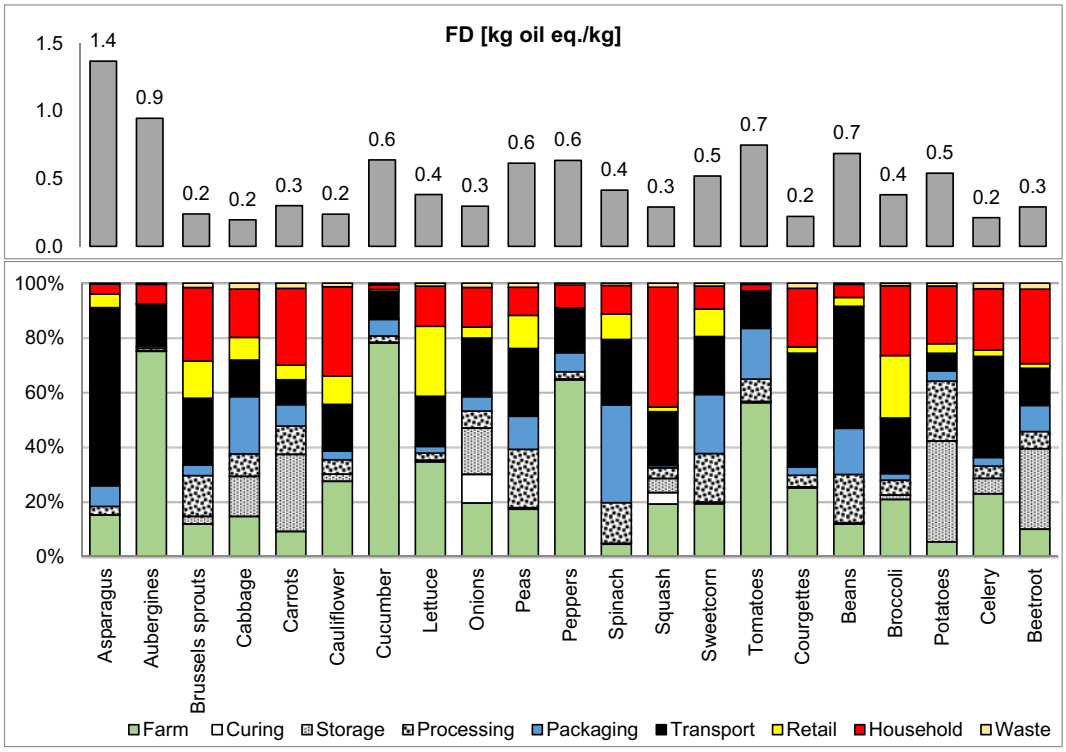


Fig. 8. Fossil depletion (FD) of vegetables and contribution of different life cycle stages.

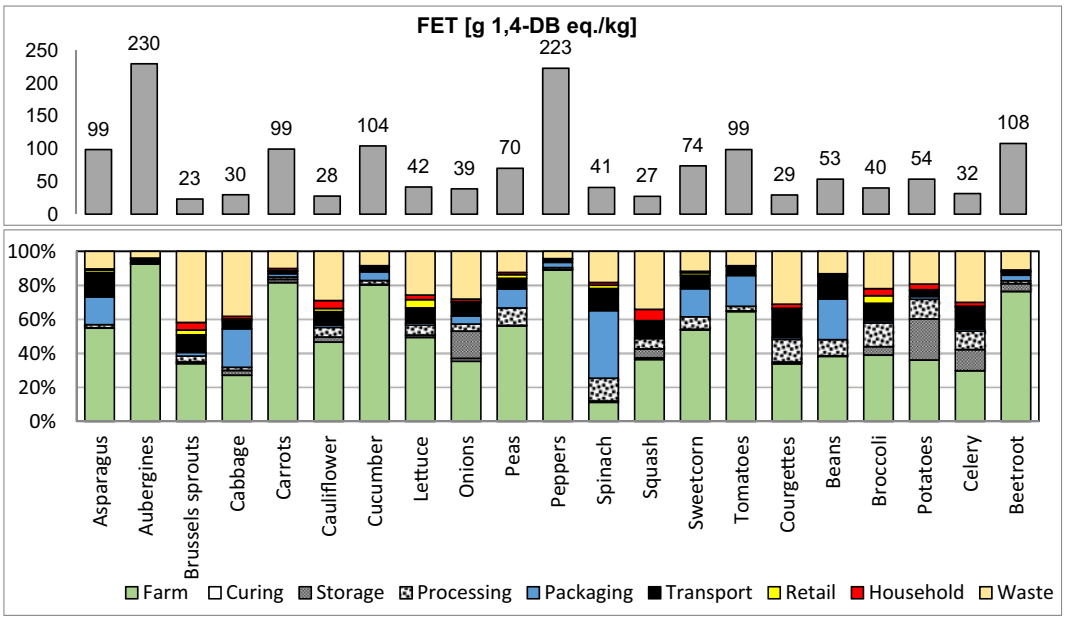


Fig. 9. Freshwater eco-toxicity (FET) and contribution of different life cycle stages.

electricity. Contribution of farming is also high for cucumber and tomatoes (79% and 61%, respectively), which have a similar impact of around 84 g 1,4-DB eq./kg. For beans, transport is the main hotspot (45%), followed by farming (29%). The MET of asparagus is largely due to cultivation (43%) and transport (21%). The disposal stage has a relatively high impact for most vegetables, with the highest impact seen for Brussels sprouts and cabbage (>40%).

3.1.6.3. Terrestrial eco-toxicity (TET). Cabbage has the lowest TET (1.8 g 1,4-DB eq./kg) and asparagus the highest (22.5 g 1,4-DB eq./kg). They are followed by sweetcorn and potatoes which have 5–10 times greater impact than the remaining vegetables (Fig. 11). Farming and transport are the main sources of TET across most of the vegetables. For example, farming causes 82% and 75% of the impact from asparagus and sweetcorn, respectively. This is due to the heavy metals in fertilisers and pesticides. The transportation impact is associated with the fuel production, with the highest TET found for courgettes, tomatoes and beans. Processing is significant for potatoes owing to the rapeseed oil used for crisps.

3.1.7. Human toxicity (HT)

For this impact, the best vegetable is Brussels sprouts with 0.39 kg 1,4-DB eq./kg. This is five times lower than the HT of asparagus (1.99 kg 1,4-DB eq./kg). Aubergines and peppers trail closely behind asparagus, with 1.62 and 1.52 kg 1,4-DB eq./kg, respectively (Fig. 12). Farming is the main contributor for most of the vegetables, accounting for 82% for aubergines and 76% for peppers. This is due to the impact associated with the energy use for heated greenhouses. For field grown vegetables, farm production contributes to HT due to the emissions from the use of fertilisers and pesticides. Storage is significant for

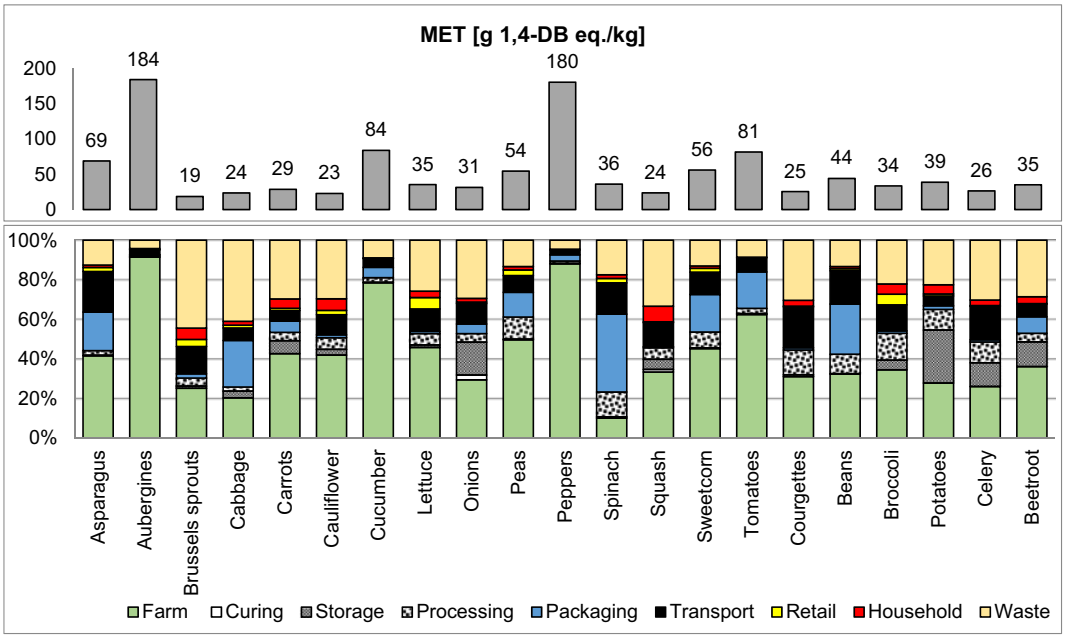


Fig. 10. Marine eco-toxicity (MET) and contribution of different life cycle stages.

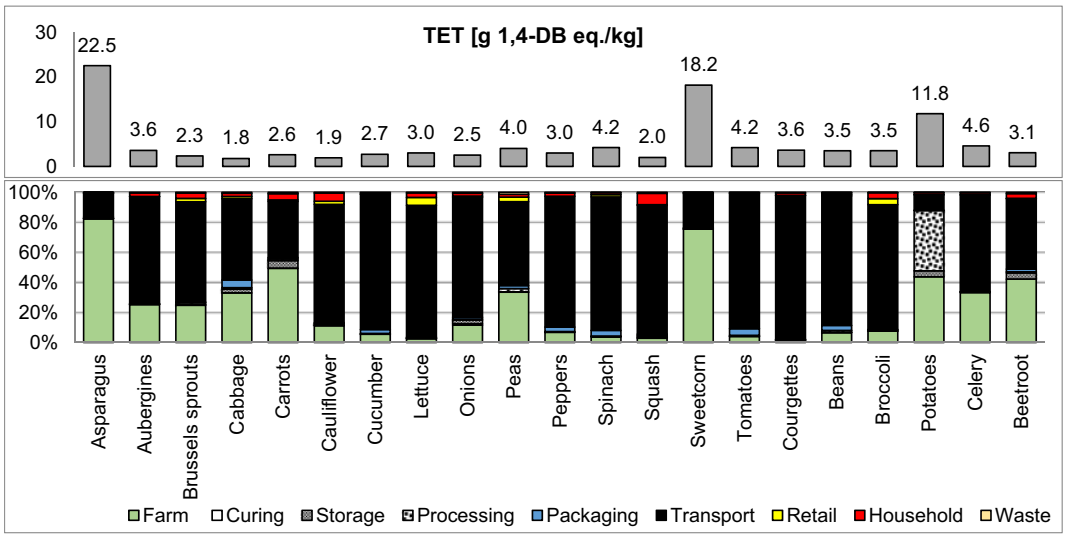


Fig. 11. Terrestrial eco-toxicity (TET) and contribution of different life cycle stages.

potatoes, causing 36% of their total HT. Packaging also contributes to the HT of spinach, sweetcorn, tomatoes and beans. Transportation is important for asparagus, tomatoes and beans. Disposal has a notable impact across the vegetables, related to heavy metal leachate from landfills, where wasted fresh produce at consumer contributes the most since most of the household waste is landfilled.

3.1.8. Eutrophication

3.1.8.1. Freshwater eutrophication (FE). Asparagus and peas have the highest FE (0.63–0.64 g P eq./kg), while the lowest impact is estimated for celery and courgettes (0.13 g P eq./kg). The contribution of different life cycle stages varies across the vegetables (Fig. 13). For instance, farming contributes 47%–72% to the impact from aubergines, peppers, tomatoes and cucumber because of the coal in the electricity mix used in greenhouses. Farm production of peas accounts for 39% of the total, with fertiliser and manure application being the main sources of FE. For potatoes, storage is responsible for 48% of the impact. Packaging contributes significantly to the FE of spinach, beans, sweetcorn, tomatoes and cabbage (21%–63%), with spinach being most affected due to the steel can production, since the majority of spinach is canned (61%). The contribution of retail is notable for lettuce and broccoli while household preparation is the main hotspot for squash and broccoli. Generally, electricity is responsible for the FE in the retail and household stages.

3.1.8.2. Marine eutrophication (ME). The highest ME is estimated again for asparagus (15.9 g N eq./kg) and the lowest for cucumber (1.2 g N eq./kg). The predominant contributor for all vegetables, except cucumber, is farm cultivation, accounting for more than 50% (Fig. 14), mainly due to nitrogen fertilisers. For cucumber, waste disposal is the hotspot with a contribution of 56%, related to landfill waste management and wastewater treatment. Disposal is also significant for all other vegetables, particularly for potatoes and lettuce.

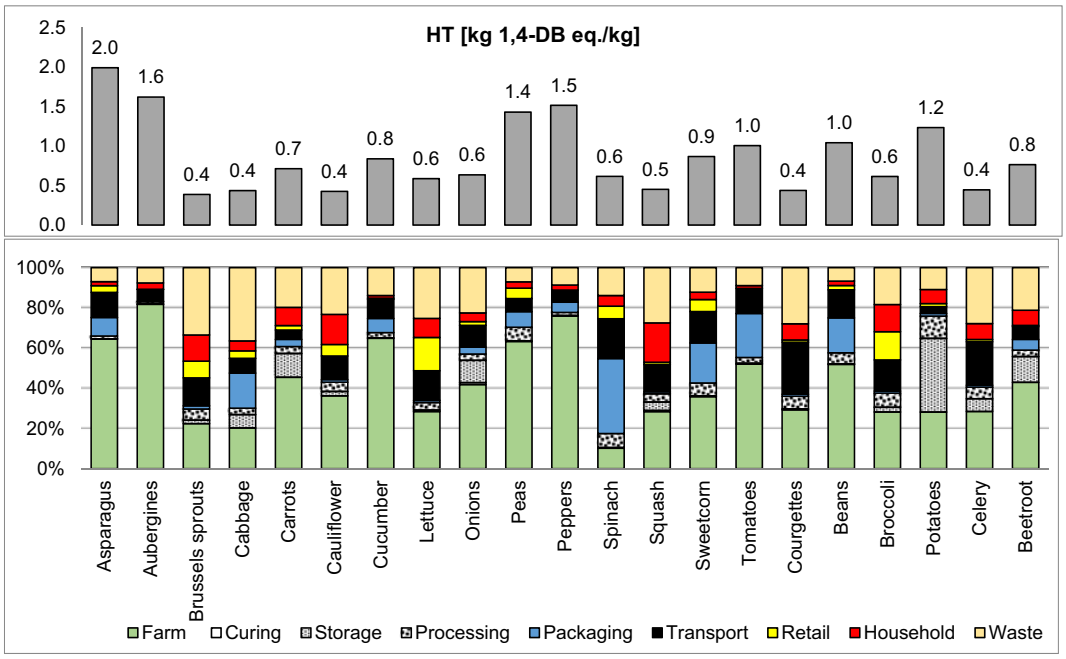


Fig. 12. Human toxicity (HT) and contribution of different life cycle stages.

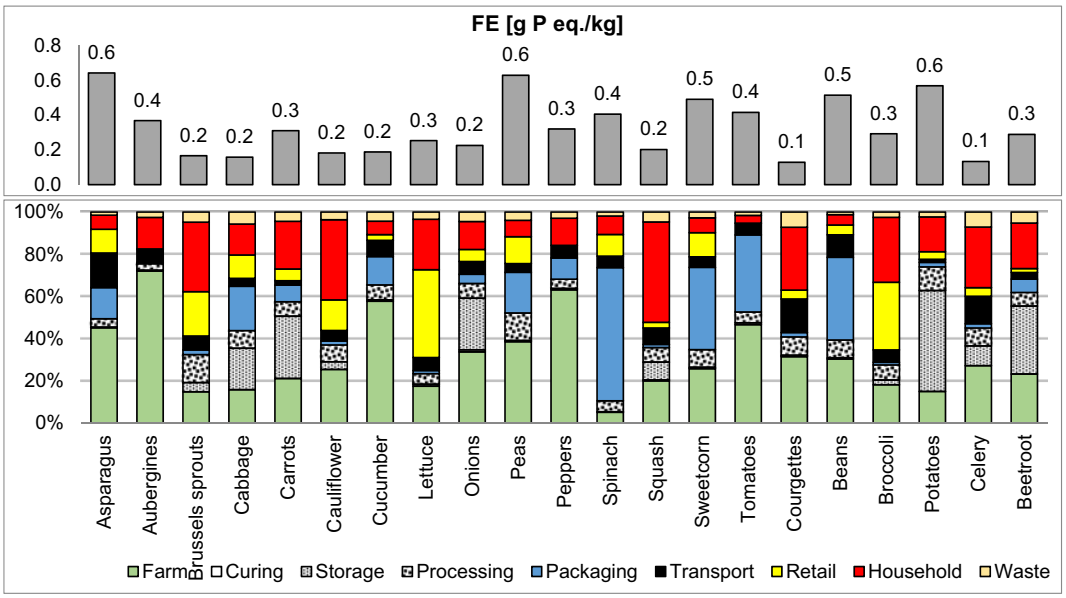


Fig. 13. Freshwater eutrophication (FE) and contribution of different life cycle stages.

3.1.9. Ionising radiation (IR)

The total IR ranges from 1.60 to 11.47 kg U235 eq./kg for cauliflower and spinach, respectively (Fig. 15). Packaging and disposal are the main contributors for most vegetables. This is due to the nuclear power in the electricity mix used for tinplate production and for wastewater treatment. Potatoes have the highest IR in the processing stage, accounting for 56% to the total. The majority of this is related to crisps, which have a nine-fold higher impact than fresh potatoes and nearly four times greater than chips (Figs. S52 and S53), largely due to the electricity used in rapeseed oil production.

3.1.10. Metal depletion (MD)

MD ranges from 19.4 to 341 g Fe eq./kg, with the highest impact found for spinach and the lowest for Brussels sprouts (Fig. 16). Farm production and packaging are the key contributors for most vegetables, followed by transport. The farming and transport impact is mainly caused by the metals used for machinery, greenhouses and vehicles. Canned vegetables have a high MD due to the use of steel, with spinach, beans, sweetcorn and peas being most affected (68%–93% of the total impact). For cabbage, packaging has the highest impact, accounting for 43% due to the glass jars used for pickles. For potatoes, storage is the main hotspot, partly due to the use of electricity for maintaining cold temperatures and partly due to the impact in the life cycle of CIPC.

3.1.11. Ozone depletion (OD)

The lowest OD is estimated for beetroot and the highest for asparagus, with the values of 0.08 and 2.84 μg CFC-11 eq./kg, respectively (Fig. 17). The retail and transportation stages are the main contributors for most vegetables due to refrigerant leakage. Transport affects the OD of squash and beans the most, contributing >85% to the total due to the large proportion of imported produce. Retail causes 90% of the OD of lettuce and 72% of the impact from broccoli. Brussels sprouts, cabbage, carrots, cauliflower, spinach and sweetcorn all have a high impact in the

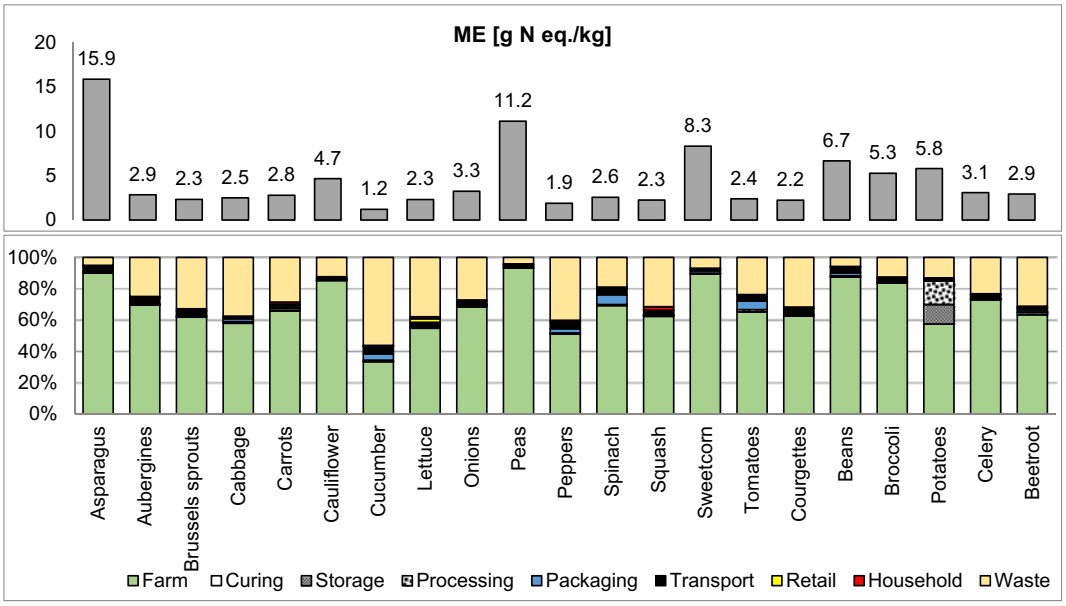


Fig. 14. Marine eutrophication (ME) and contribution of different life cycle stages.

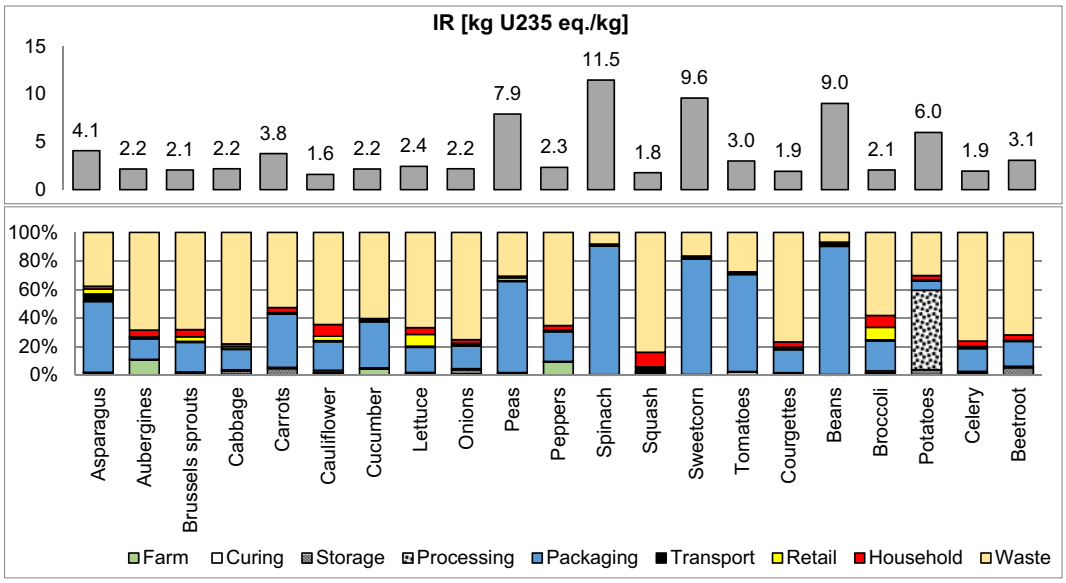


Fig. 15. Ionising radiation (IR) and contribution of different life cycle stages.

retail stage, contributing 41%–58% to the total. Vegetables grown in greenhouses cause significant OD at farm production, accounting for 56% for aubergines, 60% for cucumbers and 40% for peppers and tomatoes. For potatoes, storage contributes the majority of the impact largely due to the processed potato products, where CIPC accounts for the majority of the OD.

3.1.12. Particulate matter formation (PMF)

For this impact, cabbage is the best vegetable with 1.19 g PM_{10} eq./kg (Fig. 18). As for most other categories, asparagus is the least sustainable, with an eight-fold higher impact (8.64 g PM_{10} eq./kg). The main source of PMF is energy consumption, with farming, transport and packaging being the key hotspots across the vegetables. Transport is particularly significant for asparagus, beans, courgettes and celery, accounting for 36%–50% of the total PMF. Energy used in greenhouses contributes 48%–64% to the farming impact for aubergines, peppers, cucumber and tomatoes. Storage is a hotspot for potatoes (41%), while packaging is a notable contributor for peas, spinach, sweetcorn, tomatoes and beans (20%–57%). The household stage causes more than 20% of PMF for Brussels sprouts, cauliflower and squash.

3.1.13. Photochemical oxidants formation (POF)

A ten-fold difference is found between the lowest and highest POF across the vegetables (2.6–23 g non-methane volatile organic compounds (NMVOC)/kg). As shown in Fig. 19, the highest impact is estimated for asparagus, followed by beans, peas and sweetcorn, while cabbage has the lowest value. This impact is mainly due to the use of fuels and energy. As a result, transport is a significant contributor for most vegetables (15%–69%), with asparagus, beans, celery and courgettes being most affected owing to the high share of imported produce. Farm production causes 6%–46% of the impact, with the vegetables grown in greenhouses having the highest contribution due to the energy consumption. For vegetables grown in the field, the main contributors are mechanised field operations, such as fertilising, tillage, manure spreading and irrigation. The latter is the main source of POF in the farming stage for Spanish peas and Peruvian asparagus. For cabbage

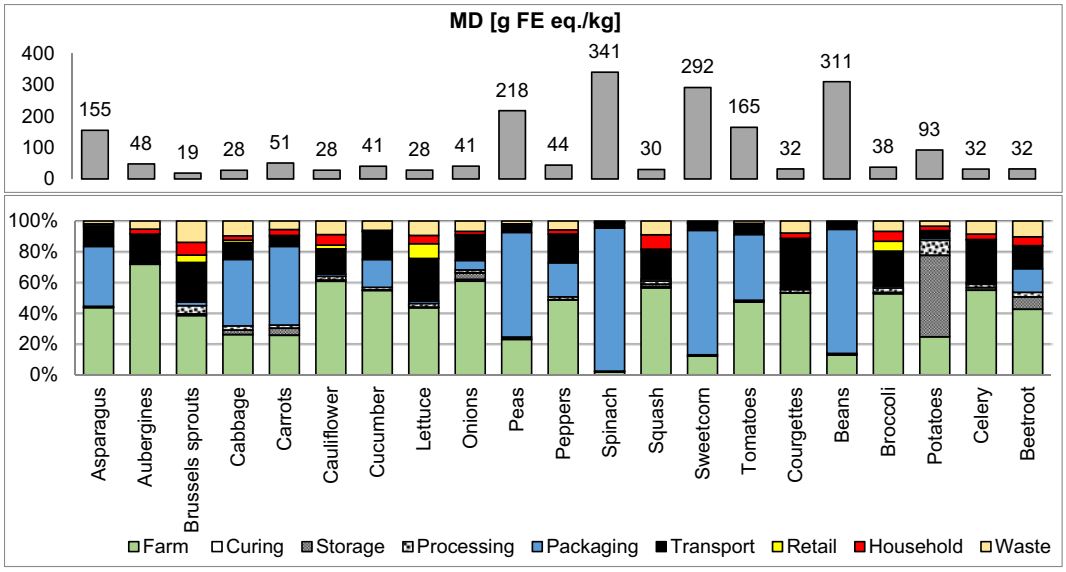


Fig. 16. Metal depletion (MD) and contribution of different life cycle stages.

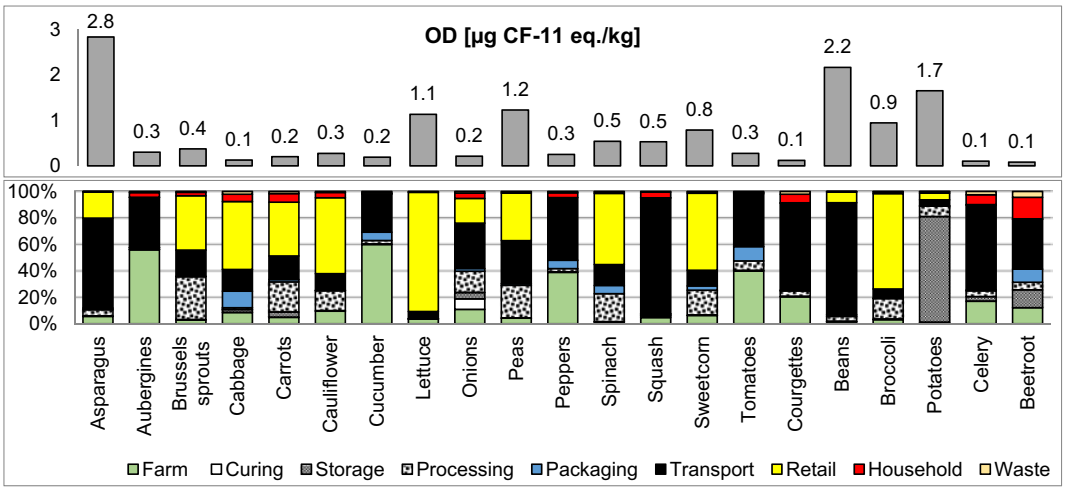


Fig. 17. Ozone depletion (OD) and contribution of different life cycle stages.

and beans grown in the Northern European countries, on the other hand, the farming impact is due to ploughing, fertiliser spreading and harvesting. The contribution of storage is significant for potatoes (36%), carrots and beetroot (19%) due to the long storage periods. Packaging has a relatively high impact for canned and pickled vegetables, contributing 17%–40% of the total.

3.1.14. Terrestrial acidification (TA)

As shown in Fig. 20, cabbage has the lowest and asparagus the highest TA (3.2 and 23 g SO_2 eq./kg, respectively). The key stages for most vegetables are farm production and transport, with some also being affected by packaging and retail storage, all related to the use of energy. For asparagus, transport accounts for 47%, followed by farm production with 38%. Transportation is a high contributor for beans (52%) due to air-freighting. Farm production causes the highest TA for the greenhouse vegetables, such as aubergines, cucumber, peppers and tomatoes (57%–71%). Farm production is also a hotspot for sweetcorn and cauliflower, contributing 62% and 50% to the total, respectively. Storage is the highest contributor for potatoes (42%). For cabbage, spinach, tomatoes and beans, packaging has a notable impact (28%–36%) due to the glass jars and cans. Retail is responsible for 23% of the impact for lettuce due to refrigeration while household consumption contributes notably to the TA of squash (23%).

3.1.15. Summary of results

To summarise the above discussion, the vegetables are ranked according to their environmental performance in a heat map in Fig. 21. The ranking is based has been obtained by assigning a score from 1 to 21 to each of the 21 vegetable types for each impact, where the best option has the lowest score and the worst alternative the highest. Vegetables with impact values within 5% of each other are assigned the same score. To obtain an overall ranking, the scores for each impact have been summed up for each vegetable applying equal weighting for the impacts.

As indicated in Fig. 21, asparagus has the highest overall score signifying the worst environmental performance, followed by beans and peas in the 20th and 19th position. Sweetcorn, tomatoes and potatoes are ranked the 18th to 16th, respectively.

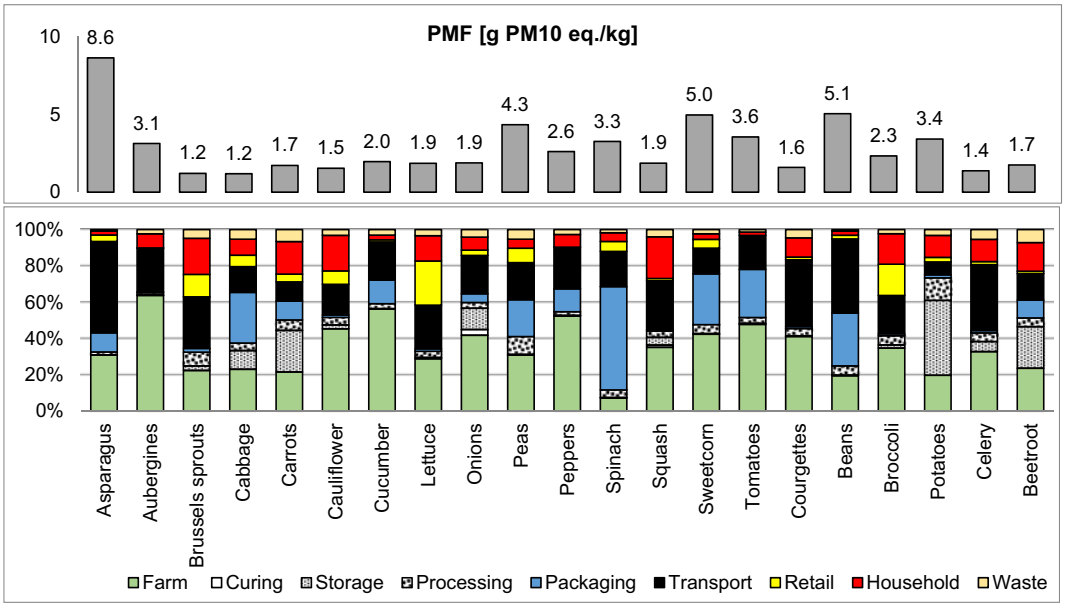


Fig. 18. Particulate matter formation (PMF) and contribution of different life cycle stages.

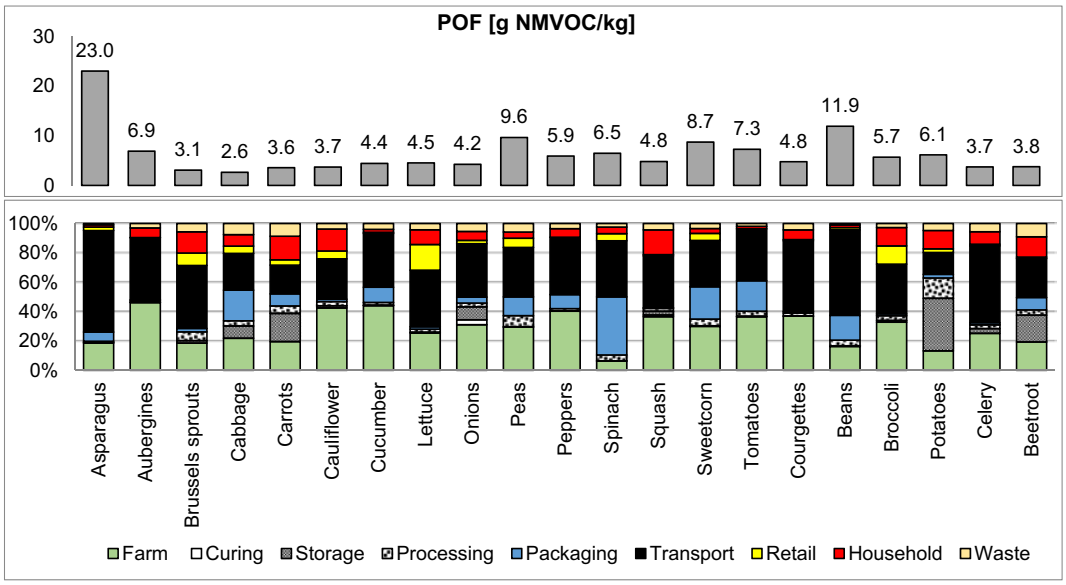


Fig. 19. Photochemical oxidants formation (POF) and contribution of different life cycle stages.

In contrast, cabbage, Brussels sprouts and courgettes have the lowest overall impact, occupying the 1st to the 3rd position, respectively. Cabbage has low scores across the impacts, but Brussels sprouts have a high OD and courgettes high TET and POF. Cauliflower, celery and squash also have low overall impact and are ranked in the 4th–6th place, respectively. However, ME and WF are high for cauliflower, squash performs worst for the WF, OD and POF, while celery has very high scores for WF, TET and ME.

The remaining nine vegetable types, ranked between the 7th and 15th place, have medium environmental impacts.

3.1.16. Comparison of results with literature

Due to a general lack of data for impacts of vegetables other than GWP and the difference in the impact methods used, the results of this work are compared only to the GWP estimated in other studies. As can be seen in Fig. 22, the values estimated in this work fall within the ranges reported in the literature. Generally, the GWP of this study is higher, since the complete supply chains are considered, also accounting for imported and processed products, which is not necessarily the case for other studies. For example, the GWP of UK tomatoes is estimated here at 12.5 kg CO_2 eq./kg which is 30% higher than the value reported by Williams et al. (2006, 2008) who only considered the impacts up to the farm gate. Furthermore, different farming practices and assumptions in the supply chain affect the results. For instance, Milà i Canals et al. (2008) estimated a greater GWP for green beans, assuming that all imported produce from Kenya and Uganda is air-freighted to the UK, while in this study 70% of the green beans are air-freighted with the rest being shipped. Similarly, the literature estimates for potatoes are higher in this work as other studies did not consider storage, which is quite significant for potatoes.

In summary, given the myriad of different assumptions and the countries of origin, the results obtained in this study compare reasonably well with the literature.

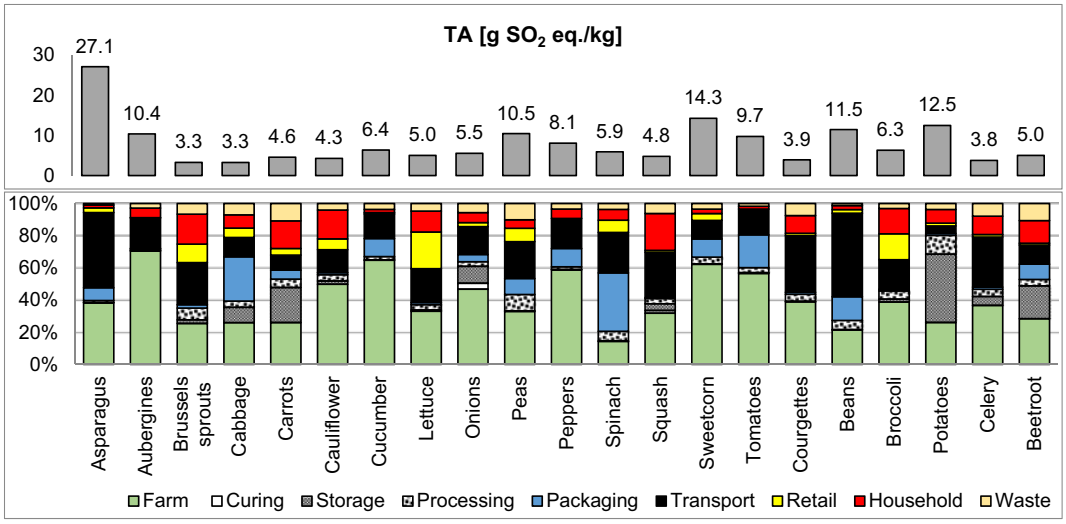


Fig. 20. Terrestrial acidification (TA) and contribution of different life cycle stages.

	Asparagus	Aubergines	Beans	Beetroot	Broccoli	Brussels sprouts	Cabbage	Carrots	Cauliflower	Celery	Courgettes	Cucumber	Lettuce	Onions	Peas	Peppers	Potatoes	Spinach	Squash	Sweetcorn	Tomatoes
Primary energy demand	21	20	16	7	10	4	1	7	7	1		15	10	5	16	16	13	10	5	14	19
Water footprint	21	7	20	5	18	7	4	2	11	18	6	2	11	11	11	1	7	17	10	11	16
Global warming	21	20	18	6	11	4	1	9	4	1	1	13	11	6	18	15	13	10	6	15	17
Agricultural land	21	4	19	15	5	3	5	14	5	5	5	1	2	13	20	5	18	5	5	17	16
Natural land	21	19	20	5	11	3	1	5	3	2	5	14	8	8	18	16	13	11	8	15	16
Urban land	21	13	19	9	11	1	2	9	2	2	5	5	8	13	17	12	13	16	5	17	19
Fossil depletion	21	20	18	6	10	4	1	6	4	2	2	15	10	6	15	15	13	12	6	13	19
Freshwater eco-toxicity	15	20	11	15	7	1	4	15	2	6	4	15	7	7	13	20	11	7	2	14	15
Marine eco-toxicity	17	20	14	9	9	1	2	7	2	5	5	18	9	8	15	20	13	9	2	15	18
Terrestrial eco-toxicity	21	11	11	8	11	4	1	5	2	18	11	5	8	5	15	8	19	15	2	20	15
Human toxicity	21	20	15	12	7	1	2	11	2	2	2	13	7	7	18	19	17	7	2	13	15
Freshwater eutrophication	20	14	17	10	10	4	3	12	5	1	1	5	9	8	20	12	19	15	7	17	15
Marine eutrophication	21	10	18	10	16	3	3	10	15	13	3	1	3	14	20	2	17	3	3	19	3
Ionising radiation	16	5	19	13	5	5	5	15	1	3	3	5	11	5	18	11	17	21	2	20	13
Metal depletion	16	13	20	6	9	1	2	14	2	6	6	10	2	10	18	12	15	21	5	19	17
Ozone depletion	21	11	20	1	16	12	4	6	9	2	3	5	17	7	18	8	19	13	13	15	9
Particulate matter	21	14	19	6	12	1	1	6	4	3	4	8	8	8	18	13	14	14	8	19	14
Photochemical oxidants	21	16	20	3	12	2	1	3	3	3	10	7	7	7	19	12	12	15	10	18	17
Terrestrial acidification	21	16	18	6	12	1	1	6	5	3	3	12	6	10	16	14	19	11	6	20	15
Total score	378	273	332	152	202	62	44	162	88	96	80	169	154	158	323	231	282	232	107	311	288
Overall ranking	21	15	20	7	12	2	1	10	4	5	3	11	8	9	19	13	16	14	6	18	17
Legend	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21
	Best									Neutral										Worst	

Fig. 21. Ranking of vegetables at the product level according to their environmental performance. [The ranking refers to the market mix of different products within each type of vegetable].

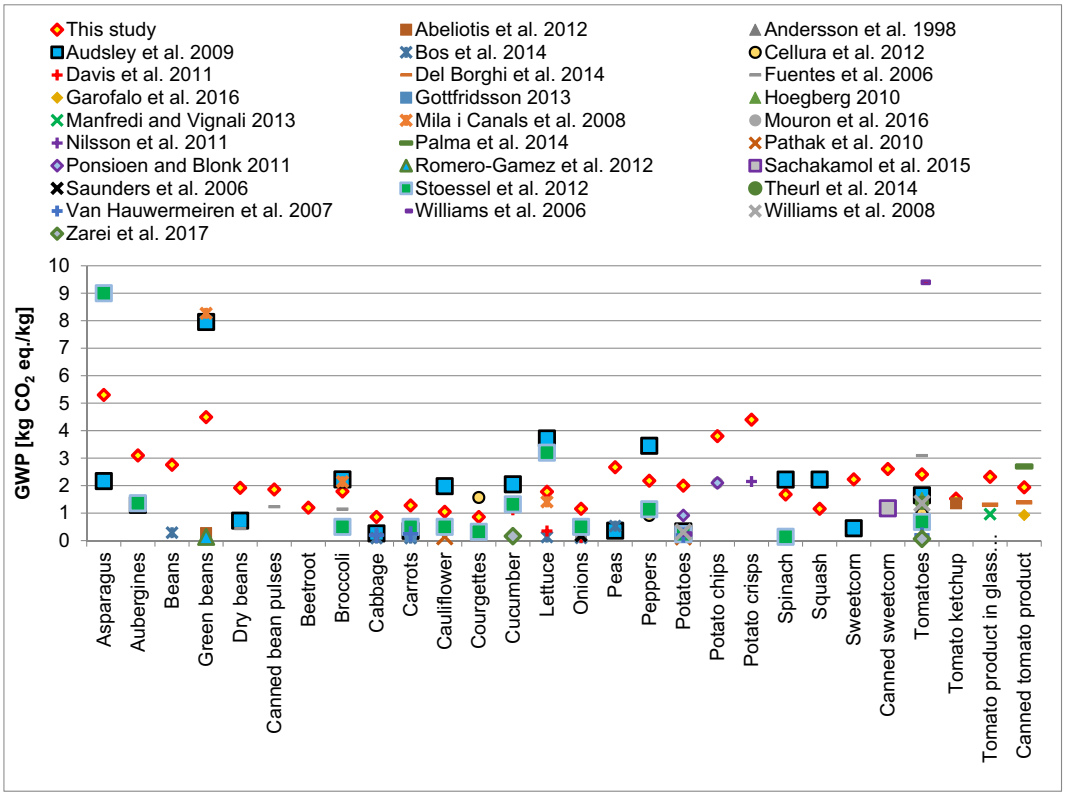


Fig. 22. Global warming potential of vegetables reported in the literature compared to the estimates obtained in this study. [Abeliotis et al., 2013; Andersson et al., 1998; Bos et al., 2014; Cellura et al., 2012; Davis et al., 2011; Del Borghi et al., 2014; Audsley et al., 2009; Fuentes et al., 2006; Garofalo et al., 2017; Gottfridsson, 2013; Hogberg, 2010; Manfredi and Vignali, 2014; Milà i Canals et al., 2008; Mouron et al., 2016; Nilsson et al., 2011; Palma et al., 2014; Pathak et al., 2010; Ponsioen and Blonk, 2011; Sachakamol and Ngarmsa-ard, 2015; Saunders et al., 2006; Stoessel et al., 2012; Theurl et al., 2014; Van Hauwermeiren et al., 2007; Williams et al., 2006; Williams et al., 2008; Zarei et al., 2018. The literature data correspond to individual products while the impacts in this study refer to a UK market mix of different products, unless indicated otherwise in the graph.]

3.2. Annual impacts at the sectoral level

The impacts estimated per kg of vegetables discussed in the previous sections have been scaled up to the sectoral level using their annual consumption given in Table 1. The total estimated impacts and the contribution of different vegetables are given in Fig. 23. For example, the sector uses 260.7 PJ of primary energy and generates 20.3 Mt CO_2 eq. annually. Considering that the whole food and drink sector in the UK consumes 1015.7 PJ/yr (DECC, 2016) and emits 176 Mt CO_2 eq. (Tassou 2014), the PED and GWP of the vegetables sector represent 26% and 11.5% of the total, respectively. However, these contribution estimates should be treated with caution due to the different assumptions and methods used in the literature to estimate the PED and GWP of the food and drink sector. It is not possible to put the other impacts in context due to a lack of data.

As can be seen in Fig. 23, the majority of the GWP and PED are caused by potatoes (57%–59%). This is proportional to the quantity of potatoes consumed in the UK, which represent 56% of the total amount of vegetables. The other notable contributors to these two impacts are tomatoes, beans, peas, carrots and onions. Tomatoes and beans amount to 4.7% and 4.4% of the vegetables sector by mass; however, they cause 6%–7% of the total GWP and PED. On the other hand, although carrots and onions account for 8% and 7.3% of the vegetables consumed, their contributions to the sectoral GWP are 5.4% and 4.5%, and to the PED 6.1% and 4.9%, respectively.

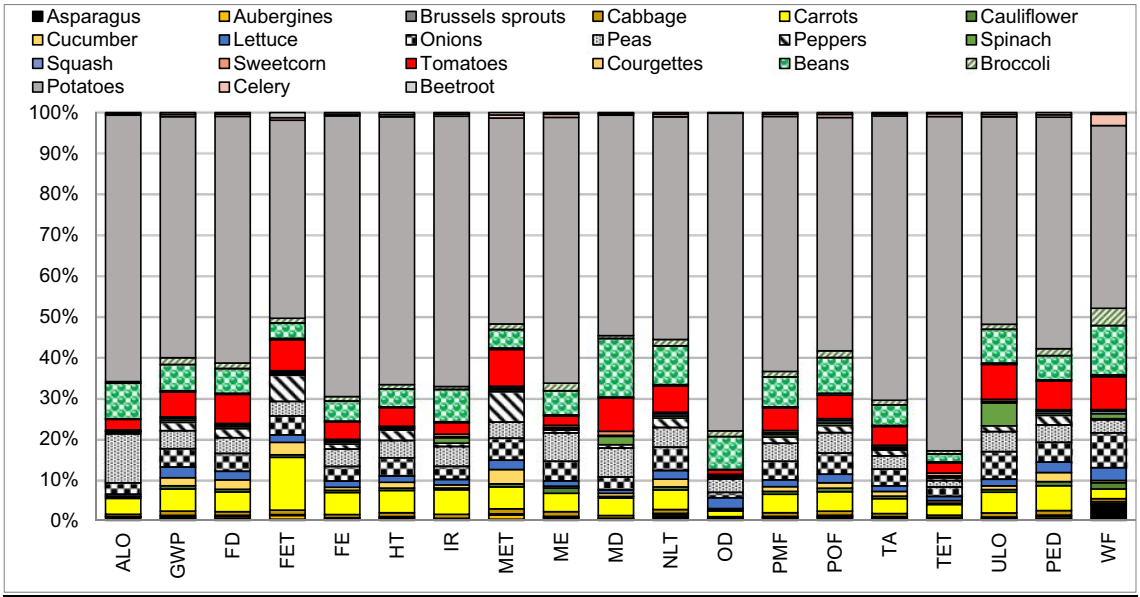
Potatoes also have the highest contribution to all the other impacts. Beans are the second highest contributors for eight impacts (GWP, IR, MD, NLT, OD, PMF, POF and TA), with the contribution ranging from 5.1% to 14%. Carrots and tomatoes are the second highest contributors to three categories each: carrots to FET, FE and HT (5.4%–13%) and tomatoes to FD, MET and ULO (7%–9%). Peas have the second highest ALO and ME (12%).

The vegetables sector requires 0.92 Mha of agricultural land annually, which is equivalent to 6% of the total land use in the UK, including arable land, industrial crops and meadows. Considering only the arable land for food crops, this represents 17% of the total land in the UK (eurostat, 2013). The WF is estimated at 253 Mm^3 eq./yr, with potatoes contributing 45%. Beans account for 12%, followed by tomatoes and onions with around 8% each. Although asparagus represents 0.2% of the vegetables consumption, it is responsible for 4% of the sectoral WF. Similarly, broccoli accounts for 4% of the annual WF, although it only amounts to 1.8% of the vegetables consumed in the UK. In contrast, carrots and peppers have a relatively low sectoral WF compared to the consumed quantities, contributing 2.4% and 0.3%, respectively.

If, hypothetically, all the vegetables were produced in the UK with no imports, the total annual PED of the vegetables sector would increase by 7% and GWP by 4%. While avoiding additional transportation, in particular air-freighting, would decrease the PED and GHG emissions by more than 50%, the use of heated greenhouses would increase these impacts, largely due to the tomato cultivation. FD, FET and MET would also increase (4%–8%). However, the water footprint would decrease by 41% along with the remaining impacts, which would be reduced by 2%–39%.

3.3. Improvement opportunities

Based on the results of the study, the environmental hotspots that should be targeted for improvements include farm production, processing, storage, packaging, transport and household cooking. Different



Annual impacts					
Agricultural land occupation (ALO)	0.92 Mha·a	Ionising radiation (IR)	54 Mt U235 eq.	Particulate matter formation (PMF)	32.8 kt PM_{10} eq.
Global warming potential (GWP)	20.3 Mt CO_2-eq.	Marine eco-toxicity (MET)	460 kt 1,4-DB eq.	Photoch. oxidants formation (POF)	64.5 kt NMVOC
Fossil depletion (FD)	5.4 Mt oil eq.	Marine eutrophication (ME)	53.6 kt N-eq.	Terrestrial acidification (TA)	107.4 kt SO_2 eq.
Freshwater eco-toxicity (FET)	660 kt 1,4-DB eq.	Metal depletion (MD)	1.03 Mt Fe eq.	Terrestrial eco-toxicity (TET)	86.4 kt 1,4-DB eq.
Freshwater eutrophication (FE)	5.0 kt P eq.	Natural land transf. (NLT)	329 ha	Urban land occupation (ULO)	15,500 ha·a
Human toxicity (HT)	11.3 Mt 1,4-DB eq.	Ozone depletion (OD)	12.8 t CFC-11 eq.	Primary energy demand (PED)	260.7 PJ
Water footprint (WF)	253 Mm^3 eq.				

Fig. 23. Annual environmental impacts of the UK vegetables sector and contribution of different vegetables.

improvement opportunities for these life cycle stages are discussed in turn below.

The main sources of impacts from farm production are fertilisers, pesticides and heated greenhouses. The impacts from the first two can be reduced through their more efficient use or via multiple cropping systems (Li et al., 2018). Using combined heat and power (CHP) generation, renewable fuels or heat from waste would also reduce most environmental impacts related to greenhouses (Davis et al., 2011; Sonesson et al., 2010).

Processed vegetables are a good alternative to fresh produce as they have longer shelf life and therefore generate less waste compared to fresh vegetables. However, this involves energy intensive processing, such as frying, freezing or concentrating, which increases the impacts of processed products. These can be reduced through energy efficiency measures (Schmidt Rivera and Azapagic, 2016), such as heat integration and utilisation of waste process heat, as well as by using CHP systems and energy from renewable sources. Recovery of energy from waste processed vegetables, for instance via anaerobic digestion, would also reduce most impacts (Slorach et al., 2019).

Storage is significant for vegetables stored over long periods due to the energy demand to ensure constant temperatures and humidity. However, most storage facilities are poorly built and not energy efficient. Therefore, improving the efficiency of storage facilities, along with the use of renewable energy, would reduce the impacts of vegetables such as potatoes, carrots, onions and beetroot. Open display refrigeration cabinets at retailers are also inefficient and result in high energy use and refrigerant leakage. Replacing those by closed-doors cabinets would be more sustainable, as is common practice in many other European countries. Furthermore, replacing currently most-commonly used refrigerant (R-404A) with those that have lower GWP (e.g. R-134A or ammonia) would help reduce the climate change impact from refrigerated storage (Schmidt Rivera and Azapagic, 2016).

Pickled and canned vegetables have higher impacts than other vegetable products largely due to the packaging, particularly glass jars and steel cans. Therefore, increasing the recycling rates and reducing energy consumption in their manufacture would help to reduce the overall impacts from vegetables. Replacing glass and steel by plastics would also reduce the impacts (Amienyo et al., 2013) but could make the packaging less recyclable. Furthermore, PET punnets also have notable impacts and should be targeted for recycling or replacement with alternative materials, such as recycled moulded pulp packaging (Belley, 2011).

Air-freighted vegetables have very high impacts and should be avoided, using sea shipping instead where possible. Alternatively, fresh air-freighted products can be replaced by processed vegetables as they have lower impacts. On the other hand, fresh vegetables transported within Europe in refrigerated trucks are environmentally better than their UK equivalents produced in heated greenhouses. Furthermore, importing vegetables from water-stressed countries should also be avoided. For instance, growing aubergines in the UK generates higher GHG emissions than importing it from within Europe, despite the additional road transport. However, sourcing aubergines from Spain, which is cultivated in unheated greenhouses, increases the water footprint, since Spain is a water-stressed country. Instead, importing aubergines from Italy would be a better alternative for both climate change and the water footprint.

At the household level, the improvement opportunities include reducing the avoidable food waste, using more efficient cooking appliances (gas ovens and hobs or microwaves) and eating in-season vegetables to avoid air-freighting and greenhouse production. Furthermore, increasing household recycling rates and reducing landfilling would improve further the environmental performance of vegetables. This is also stipulated by the EU Circular Economy Action Plan which aims to increase the recycling rate of municipal waste to 65% and reduce landfilling to 10% by 2035 (European Commission, 2019). Reducing and recycling waste in the rest of the supply chain would also help towards a greater sustainability of the vegetables sector and the implementation of the circular economy.

4. Conclusions

The impacts of vegetables consumed in the UK have been assessed on a life cycle basis considering both UK and imported produce at the product and sectoral levels. It total, 19 LCA impacts have been estimated for 21 vegetable types and their 56 products.

The annual consumption of vegetables in the UK requires 260 PJ of primary energy and 253 Mm^3 eq. of water and emits 20.3 Mt CO_2 eq. At a sectoral level, potatoes contribute more than 50% across the impact categories. This is due to their high consumption and particularly due to the energy used in the production of crisps and chips. Other significant contributors to sectoral impacts are beans, tomatoes, carrots and peas. In addition to potatoes, beans, tomatoes, onions, asparagus and broccoli contribute most to the water footprint.

At the product level, asparagus has the highest impacts in 14 categories (ALO, GWP, FD, HT, FE, ME, NLT, OD, PMF, POF, TA, TET, PED, WF). Beans have the second highest impact in six categories (MD, POF, PMF, OD, NLT, ULO) and aubergines and spinach perform worst in two categories each: FET and MET for the former and IR and MD for the latter. Celery is the best vegetable for PED and GWP and peppers for the WF. Overall, cabbage performs best in six categories (FD, NLT, PMF, POF, TA, TET), while Brussels sprouts have the lowest impact in four categories (MD, FET, MET, ULO).

The air-freighted vegetables have the highest impacts, followed by frozen products. For instance, fresh asparagus flown to the UK has three times higher impacts than frozen or canned asparagus produced domestically. Fresh vegetables tend to have the lowest impacts if they are not air-freighted. Importing vegetables from Europe grown in unheated greenhouses has a lower impact than UK vegetables cultivated in heated greenhouses, despite the (road) transportation.

Farm production is the main hotspot for ALO, ULO, HT, FET, ME and TA. It also contributes substantially to most impact categories for the vegetables grown in heated greenhouses. Storage is significant for vegetables stored over a long period, such as carrots and potatoes, where refrigeration and post-harvest treatment with pesticides are the main contributors. Energy intensive processing, such as freezing, pasteurising and frying, as well as additional ingredients (e.g. oil), have significant impacts in the processing stage. Energy consumption in the retail and household stages is a hotspot for PED, GWP, FD, FE and TA. Canned and pickled vegetables tend to have higher MD, GWP, PED and FE. Transportation is the main source of OD, PMF, POF and TET, with air transport being a hotspot for most categories. Waste disposal contributes notably to GWP, FET, HT, IR, MET, ME and ULO. Thus, targeting these hotspots would help to reduce the environmental impacts across the vegetables supply chain.

Future work should examine in more detail various improvement opportunities mentioned in this work to quantify the environmental savings that could be achieved at the sectoral level. Further studies should also consider the economic and social sustainability of vegetables. This work could also be complemented with sustainability studies of vegetable products in other countries and regions. It is expected that the current and any further work on this topic will be of interest to vegetable producers, retailers and consumers, helping them to make more informed choices towards sustainable production and consumption of food.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.scitotenv.2019.04.424.

References

Abeliotis, K., Detsis, V., Pappia, C., 2013. Life cycle assessment of bean production in the Prespa National Park, Greece. J. Clean. Prod. 41, 89–96. https://doi.org/10.1016/j.jclepro.2012.09.032.

AHDB & Potato Council, 2015. GB potatoes: market intelligence 2015–2016. https://potatoes ahdb.org.uk/sites/default/files/publication_upload/GB%20Potatoes%202015-2016.pdf.

Amienyo, D., Gujba, H., Stichnothe, H., Azapagic, A., 2013. Life cycle environmental impacts of soft carbonated drinks. Int. J. LCA 18, 77–92. https://doi.org/10.1007/s11367-012-0459-y.

Andersson, K., Ohlsson, T., 1999. Including environmental aspects in production development: a case study of tomato ketchup. LWT - Food Sci. Technol. 32, 134–141. https://doi.org/10.1006/fstl.1998.0513.

Andersson, K., Ohlsson, T., Olsson, P., 1998. Screening life cycle assessment (LCA) of tomato ketchup: a case study. Doktorsavhandlingar vid Chalmers Tek. Hogsk. 6, 1–19. https://doi.org/10.1016/S0959-6526(98)00027-4.

Assured Produce, 2008. Crop specific protocol: onions (bulb and shallots). Assured Produce, Document No: 00036/08. http://www.assuredproduce.co.uk/eblock/services/resources.ashx/000/255/645/Onions_(bulb)1.pdf.

Audsley, Eric, Brander, Matthew, Chatterton, Julia, Murphy-Bokern, Donal, Catriona Webster, A.W., 2009. How long can we go? An assessment of GHG emissions from the UK food system end and the scope to reduce them by 2050. http://assets.wwf.org.uk/downloads/how_low_report_1.pdf.

Belley, C., 2011. Comparative Life Cycle Assessment Report of Food Packaging Products. CIRAIG, Interuniversity Research Centre for the Life Cycle of Products, Processes and Services, Quebec https://www.cascades.com/media/multiuploader_images/6/12/41/LCAFoodPackagingProducts_1.pdf.

Bos, J.F.F.P., De Haan, J., Sukkel, W., Schils, R.L.M., 2014. Energy use and greenhouse gas emissions in organic and conventional farming systems in the Netherlands. NJAS - Wageningen J. Life Sci. 68, 61–70. https://doi.org/10.1016/j.njas.2013.12.003.

Bozokalfa, M.K., Kilic, M., 2010. Mathematical modeling in the estimation of pepper (Capsicum annuum L.) fruit volume. Chil. J. Agric. Res. 70, 626–632. https://doi.org/10.4067/S0718-58392010000400013.

Cachoeira-Stertz, Sônia, Santo, Espírito, Do, A.P., Bona, C., Freitas, R.J.S. De, 2005. Comparative morphological analysis of cherry tomato fruits from three cropping systems. Sci. Agric. 62, 296–298. https://doi.org/10.1590/S0103-90162005000300015.

Carlsson-Kanyama, A., 1998. Food consumption patterns and their influence on climate change - greenhouse gas emissions in the life-cycle of tomatoes and carrots consumed in Sweden. Springer, Royal Swedish Academy of Sciences 27, 528–534. https://doi.org/10.2307/4314785.

Cellura, M., Ardente, F., Longo, S., 2012. From the LCA of food products to the environmental assessment of protected crops districts: a case-study in the south of Italy. J. Environ. Manag. 93, 194–208. https://doi.org/10.1016/j.jenvman.2011.08.019.

Dargan, A.E., 2011. Environmental Impact Analysis in Apple and Pineapple Juices Concentrates Supply Chains. Wageningen University, Amsterdam http://edepot.wur.nl/172035.

Davis, J., Wallman, M., Sund, V., Emanuelsson, A., Cederberg, C., Sonesson, U., 2011. Emissions of greenhouse gases from production of horticultural products - analysis of 17 products cultivated in Sweden. SIK-Swedish Institute for Food and Biotechnology. SIK-Report No Sr, 828. http://www.diva-portal.org/smash/get/diva2:943913/FULLTEXT01.pdf.

DECC, 2016. Digest of United Kingdom energy statistics (DUKES). https://www.gov.uk/government/collections/digest-of-uk-energy-statistics-dukes.

DEFRA, 2008. Greenhouse gas impacts of food retailing. DEFRA project FO0405. http://sciencesearch.defra.gov.uk/Default.aspx?Menu=Menu&Module=More&Location=None&Completed=0&ProjectID=15805.

DEFRA, 2014a. Family food statistics 2013. https://www.gov.uk/government/collections/family-food-statistics.

DEFRA, 2014b. Food statistics pocketbook 2013. https://www.gov.uk/government/statistics/food-statistics-pocketbook.

DEFRA, 2015. Horticulture statistics. https://www.gov.uk/government/statistics/latest-horticulture-statistics.

Del Borghi, A., Gallo, M., Strazza, C., Del Borghi, M., 2014. An evaluation of environmental sustainability in the food industry through life cycle assessment: the case study of tomato products supply chain. J. Clean. Prod. 78, 121–130. https://doi.org/10.1016/j.jclepro.2014.04.083.

Downes, K., Chope, G.A., Terry, L.A., 2009. Effect of curing at different temperatures on biochemical composition of onion (Allium cepa L.) skin from three freshly cured and cold stored UK-grown onion cultivars. Postharvest Biol. Technol. 54, 80–86. https://doi.org/10.1016/j.postharvbio.2009.05.005.

Durlinger, B., Koukouna, E., Broekema, R., Paassen, M. van, Scholten, J., 2017. Agri-footprint 3.0. Blonk Consultants, Gouda, NLhttp://www.agri-footprint.com.

Ecoinvent, 2010. Ecoinvent V2.2 Database. Swiss Centre for Life Cycle Inventories (Dubendorf, Switzerland).

Ecoinvent, 2015. Ecoinvent V3.1 Database. Swiss Centre for Life Cycle Inventories (Dubendorf, Switzerland).

Ecoinvent, 2016. Ecoinvent V3.3 Database. Swiss Centre for Life Cycle Inventories, Dubendorf, Switzerland.

European Commission, 2006. Directive 96/61/EC: best available techniques in the food, drink and milk industries. http://eippcb.jrc.ec.europa.eu/reference/BREF/FDM/FDM_31-01-2017-D1_b_w.pdf.

European Commission, 2019. Implementation of the Circular Economy Action Plan. http://ec.europa.eu/environment/circular-economy/index_en.htm.

eurostat, 2013. Agricultural area by land use UK 2010. http://ec.europa.eu/eurostat/statistics-explained/index.php/File:Table_Utilised_Agricultural_Area_by_land_use_UK_2000_and_2010.PNG.

FAO, 2007. Pickles. http://www.fao.org/3/a-au116e.pdf.

FAO/INFOODS, 2012. Density database. http://www.fao.org/3/ap815e/ap815e.pdf.

FAO/WHO, 2004. Fruit and Vegetables for Health. http://www.who.int/dietphysicalactivity/%0Afruit/en/index1.html.

Fidan, H., Tanrivermis, H., 2006. The changes in production and foreign trade of primary and processed tomato. Pakistan J. Biol. Sci. 9, 995–1003. https://doi.org/10.3923/pjbs.2006.995.1003.

Finglas, P.M., Roe, M.A., Pinchen, H.M., Berry, R., Church, S.M., Dodhia, S.K., Farron-Wilson, M., Swan, G., 2015. McCance and Widdowson's the Composition of Foods. Institute of Food Research, Public Health England. Royal Society of Chemistry.

Foodmiles.com, 2016. Food miles calculator. http://www.foodmiles.com.

Fresh Direct, 2018. Vegetable storage guide. https://www.freshdirect.com.

Fuentes, C., Grankvist, G., Lagerberg-Fogelberg, C., Shanahan, H., Solér, C., 2006. Environmental information in the food supply system. report number, ISRN FOI-R-1903-SE. Lund University. FOI - Swedish Defense Research Agencyhttps://portal.research.lu.se/ws/files/4687139/2834896.pdf.

Garnett, T., 2006. Fruit and vegetables & UK greenhouse gas emissions: exploring the relationship. Food Climate Research Networkhttps://www.fcrn.org.uk/sites/default/files/Fruitnveg_paper_2006.pdf.

Garofalo, P., D'Andrea, L., Tomaiuolo, M., Venezia, A., Castrignanò, A., 2017. Environmental sustainability of agri-food supply chains in Italy: the case of the whole-peeled tomato production under life cycle assessment methodology. J. Food Eng. 200, 1–12. https://doi.org/10.1016/j.jfoodeng.2016.12.007.

Gakidou, E., Afshin, A., Abajobir, A.A., Abate, K.H., Abbafati, C., Abbas, K.M., et al., 2017. Global, regional, and national comparative risk assessment of 84 behavioural, environmental and occupational, and metabolic risks or clusters of risks, 1990-2016: a systematic analysis for the Global Burden of Disease Study 2016. Lancet https://doi.org/10.1016/S0140-6736(17)32366-8.

Geeta, H.P., Palanimuthu, V., Srinivas, G., 2017. Study of some physico-chemical properties of sweet corn. Int. J. Agric. Sci. Res. 7, 277–286.

George DeLallo Company, 2014. Canned tomatoes. https://www.delallo.com.

Gerbens-Leenes, P.W., Hoekstra, A.Y., Bosman, R., 2018. The blue and grey water footprint of construction materials: steel, cement and glass. Water Resour. Ind. 19, 1–12. https://doi.org/10.1016/j.wri.2017.11.002.

Gholami, R., Lorestani, A.L., Jaliliantabar, F., 2012. Determination of physical and mechanical properties of zucchini. Agric. Eng. Int. CIGR J. 14, 136–140. http://cigrjournal.org/index.php/Ejounral/article/view/2068.

Goedkoop, M., Heijungs, R., Huijbregts, M., De Schryver, A., Struijs, J., Van Zelm, R., 2013. ReCiPe 2008: a life cycle impact assessment method which comprises harmonised category indicators at the midpoint and the endpoint level. https://www.rivm.nl/sites/default/files/2018-11/ReCiPe%202008_A%20lcia%20method%20which%20comprises%20harmonised%20category%20indicators%20at%20the%20midpoint%20and%20the%20endpoint%20level_First%20edition%20Characterisation.pdf.

González, A.D., Frostell, B., Carlsson-Kanyama, A., 2011. Protein efficiency per unit energy and per unit greenhouse gas emissions: potential contribution of diet choices to climate change mitigation. Food Policy 36, 562–570. https://doi.org/10.1016/j.foodpol.2011.07.003.

Gottfridsson, L., 2013. Global warming potential and nutritional content of fresh and frozen roots - a study on carrots and turnips. Faculty of Natural Resources and Agricultural Sciences, Department of Food Science, Swedish University of Agricultural Sciences, Uppsalahttps://stud.epsilon.slu.se/6377/7/gottfridsson_l_140304.pdf.

Heller, M., Narayanan, T., Meyer, R., Keoleian, G., 2016. Category-level Product Environmental Footprints of Foods: Food Life Cycle Assessment Literature Review. Center for Sustainable Systems, University of Michigan http://css.umich.edu/publication/category-level-product-environmental-footprints-foods-food-life-cycle-assessment.

Hendricks, P., 2012. Life cycle assessment of greenhouse tomato (Solanum lycopersicum L.) production in Southwestern Ontario. University of Guelph. https://atrium.lib.uoguelph.ca/xmlui/bitstream/handle/10214/4052/Life%20Cycle%20Assessment%20of%20Greenhouse%20Tomato%20(Solanum%20lycopersicum%20L.)%20Production%20in%20Southwestern%20Ontario.pdf?sequence=1.

Hogberg, J., 2010. European tomatoes. Environmental systems analysis. Chalmers University of Technology, Gothenburg, Swedenhttp://publications.lib.chalmers.se/records/fulltext/141466.pdf.

Hospido, A., Milà, I., Canals, L., McLaren, S., Truninger, M., Edwards-Jones, G., Clift, R., 2009. The role of seasonality in lettuce consumption: a case study of environmental and social aspects. Int. J. Life Cycle Assess. 14, 381–391. https://doi.org/10.1007/s11367-009-0091-7.

IPCC, 2007. Climate Change 2007: Mitigation of Climate Change. Contribution of Working Group III to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

ISO, 2006a. ISO 14040:2006 Environmental Management - Life Cycle Assessment -Principles and Framework. BSI, London.

ISO, 2006b. ISO 14044:2006 Environmental management - Life cycle assessment -Requirements and guidelines. BSI, London.

ITC, 2015. Market analysis and research international trade centre. www.intracen.org.

Jha, S.N., Matsuoka, T., 2002. Surface stiffness and density of eggplant during storage. J. Food Eng. 54, 23–26. https://doi.org/10.1016/S0260-8774(01)00181-9.

Kraft Heinz group, 2018. Tomato ketchup. https://www.heinz.co.uk.

Li, L., Wu, W., Giller, P., O'Halloran, J., Liang, L., Peng, P., Zhao, G., 2018. Life cycle assessment of a highly diverse vegetable multi-cropping system in Fengqiu County, China. Sustain 10, 1–17. https://doi.org/10.3390/su10040983.

Macdiarmid, J., Kyle, J., Horgan, G., Loe, J., Fyfe, C., Johnstone, A., McNeill, G., 2011. Livewell: A Balance of Healthy and Sustainable Food Choices. WWF-UK Report, Surrey. http://assets.wwf.org.uk/downloads/livewell_report_jan11.pdf.

Machine & Process Design, 2015. Bulk density. http://www.mpd-inc.com.

Manfredi, M., Vignali, G., 2014. Life cycle assessment of a packaged tomato puree: a comparison of environmental impacts produced by different life cycle phases. J. Clean. Prod. 73, 275–284. https://doi.org/10.1016/j.jclepro.2013.10.010.
Marriott, C., 2005. From Plough to Plate by Plane. An Investigation Into Trends and Drivers in the Airfreight Importation of Fresh Fruit and Vegetables into the United Kingdom from 1996 to 2004. Centre for Environmental Strategy, University of Surrey.
Masanet, E., Worrell, E., Graus, W., Galitsky, C., 2008. Energy Efficiency Improvement and Cost Saving Opportunities for the Fruit and Vegetable Processing Industry. University of California, Berkeley https://www.energystar.gov/sites/default/files/buildings/tools/Food-Guide.pdf.
Mccarthy, K.L., Mccarthy, A.J., 2009. Relationship between in-line viscosity and Bostwick measurement during ketchup production. J. Food Sci. 74, 291–297. https://doi.org/10.1111/j.1750-3841.2009.01205.x.
Mekonnen, M.M., Hoekstra, A.Y., 2010. The Green, Blue and Grey Water Footprint of Crops and Derived Crop Products. Value of Water, Research Report Series No. 47. UNESCO-IHE Institute for Water Education, Delft, The Netherlands.
Milà i Canals, L., Munoz, I., Mclaren, S.J., Brandão, M., 2007. LCA methodology and modelling considerations for vegetable production and consumption. RELU project RES-224-25-0044 https://www.surrey.ac.uk/ces/files/pdf/0207_LCA_Methodol_and_LCI_Model_RELU.pdf.
Milà i Canals, L., Muñoz, I., Hospido, A., Plassmann, K., McLaren, S., 2008. Life cycle assessment (LCA) of domestic vs. imported vegetables. Case studies on broccoli, salad crops and green beans. RELU project REW-224-25-0044 http://www2.surrey.ac.uk/ces/files/pdf/0108_CES_WP_RELU_Integ_LCA_local_vs_global_vegs.pdf.
Mouron, P., Willersinn, C., Möbius, S., Lansche, J., 2016. Environmental profile of the swiss supply chain for French fries: effects of food loss reduction, loss treatments and process modifications. Sustain 8, 1214–1224. https://doi.org/10.3390/su8121214.
Mousavizadeh, S.J., Mashayekhi, K., 2010. Evaluation of some physical properties of cucumber (Cucumis sativus L.). J. Agric. Sci. Technol. 4, 300–315. https://doi.org/10.1016/j.inpa.2017.07.001.
Nilsson, K., Sund, V., Floren, B., 2011. The environmental impact of the consumption of sweets, crisps and soft drinks, Nordic cooperation. Nordic Council of Ministers, Copenhagenhttp://www.diva-portal.org/smash/get/diva2:702819/FULLTEXT01.pdf.
Noonari, S., Memon, M.S., 2015. Performance of pickle production processing and marketing in Sindh Pakistan. J. Food Process. Technol. 6, 72–79. https://doi.org/10.4172/2157-7110.1000523.
Oyebode, O., Gordon-Dseagu, V., Walker, A., Mindell, J.S., 2014. Fruit and vegetable consumption and all-cause, cancer and CVD mortality: analysis of health survey for England data. J. Epidemiol. Community Health 68, 856–862. https://doi.org/10.1136/jech-2013-203500.
Palma, G., Padilla, M., Saheb, M., Tatar, Y., Tugulay, A., Kellou, I., Colvine, S., 2014. Environmental impact of processed tomato in France and in Turkey. Proc. 9th Int. Conf. Life Cycle Assess. Agri-Food Sect. (LCA Food 2014), San Fr. California, USA, 8–10 October, 2014, pp. 948–952.
Palmer, J., Terry, N., Kane, T., Firth, S., Hughes, M., Pope, P., Young, J., Knight, D., Godoy-Shimizu, D., 2013. Electrical Appliances at Home: Tuning in to Energy Savings.
Pathak, H., Jain, N., Bhatia, A., Patel, J., Aggarwal, P.K., 2010. Carbon footprints of Indian food items. Agric. Ecosyst. Environ. 139, 66–73. https://doi.org/10.1016/j.agee.2010.07.002.
Payen, S., Basset-Mens, C., Perret, S., 2015. LCA of local and imported tomato: an energy and water trade-off. J. Clean. Prod. 87, 139–148. https://doi.org/10.1016/j.jclepro.2014.09.007.
PE International, 2014. GaBi Database V6 Software and Database. www.pe-international.com.
Pfister, S., Koehler, A., Hellweg, S., 2009a. Assessing the environmental impacts of freshwater consumption in LCA - supporting information. Environ. Sci. Technol. 43, 4098–4104. https://doi.org/10.1021/es802423e.
Pfister, S., Koehler, A., Hellweg, S., 2009b. Assessing the environental impact of freshwater consumption in life cycle assessment. Environ. Sci. Technol. 43, 4098–4104. https://doi.org/10.1021/es802423e.
PlasticsEurope, 2016. Packaging. https://www.plasticseurope.org.
Ponsioen, T., Blonk, H., 2011. Case studies for more insight into the methodology and composition of carbon footprints of table potatoes and chips. Blonk Environmental Consultants, CA Goudahttp://www.blonkconsultants.nl/wp-content/uploads/2016/06/Carbon-footprints-of-table-potatoes-and-chips-July-2011.pdf.
Ports.com, 2018. Sea route & distance. http://ports.com.
Potato Industry CIPC Stewardship Group (PICSG), 2018. About CIPC. http://www.cipccompliant.co.uk.
Pydynkowski, K., 2008. A Life Cycle Analysis for Tomatoes in NH. Thayer School of Engineering, Dartmouth College, New Hampshire, USA http://www.dartmouth.edu/~cushman/courses/engs171/Tomatoes.pdf.
Rizzo, V., Muratore, G., 2009. Effects of packaging on shelf life of fresh celery. J. Food Eng. 90, 124–128. https://doi.org/10.1016/j.jfoodeng.2008.06.011.
Röös, E., Karlsson, H., 2013. Effect of eating seasonal on the carbon footprint of Swedish vegetable consumption. J. Clean. Prod. 59, 63–72. https://doi.org/10.1016/j.jclepro.2013.06.035.
Roy, P., Nei, D., Okadome, H., Nakamura, N., Orikasa, T., Shiina, T., 2008. Life cycle inventory analysis of fresh tomato distribution systems in Japan considering the quality aspect. J. Food Eng. 86, 225–233. https://doi.org/10.1016/j.jfoodeng.2007.09.033.
Sachakamol, P., Ngarmsa-ard, P., 2015. Life cycle assessment of canned sweet corn in Chiang Mai. Proceedings of the MakeLearn and TIIM Joint International Conference, Bari-Italy, 27–29 May 2015, pp. 1093–1101.
Saunders, C., Barber, A., Taylor, G., 2006. Food miles – comparative energy/emissions performance of New Zealand's agriculture industry. AERU Research Report No. 285 https://ucanr.edu/datastoreFiles/608-324.pdf.
Schmidt Rivera, X., Azapagic, A., 2016. Life cycle costs and environmental impacts of production and consumption of ready and home-made meals. J. Clean. Prod. 112, 214–228. https://doi.org/10.1016/j.jclepro.2015.07.111.
Slorach, P.C., Jeswani, H.K., Cuellar-Franca, R., Azapagic, A., 2019. Environmental sustainability of anaerobic digestion of household food waste. J. Environ. Management 236, 798–814. https://doi.org/10.1016/j.jenvman.2019.02.001.
Sonesson, Ui, Davis, J., Ziegler, F., 2010. Food Production and Emissions of Greenhouse Gases. An Overview of the Climate Impact of Different Product Groups. SIK-Swedish Institute for Food and Biotechnology SIK-Report No 802 2010. http://www.diva-portal.org/smash/get/diva2:943607/FULLTEXT01.pdf.
Stoessel, F., Juraske, R., Pfister, S., Hellweg, S., 2012. Life cycle inventory and carbon and water foodprint of fruits and vegetables: application to a Swiss retailer. Environ. Sci. Technol. 46, 3253–3262. https://doi.org/10.1021/es2030577.
Tamburini, E., Pedrini, P., Marchetti, M., Fano, E., Castaldelli, G., 2015. Life cycle based evaluation of environmental and economic impacts of agricultural productions in the Mediterranean area. Sustainability 7, 2915–2935. https://doi.org/10.3390/su7032915.
Tassou, S.A., 2014. Energy demand and reduction opportunities in the UK food chain. Energy 167, 162–170. https://doi.org/10.1680/ener.14.00014.
Theurl, M.C., Haberl, H., Erb, K.H., Lindenthal, T., 2014. Contrasted greenhouse gas emissions from local versus long-range tomato production. Agron. Sustain. Dev. 34, 593–602. https://doi.org/10.1007/s13593-013-0171-8.
Toivonen, P., Forney, C., 2004. Brussels sprout. In: Gross, K.C., Wang, C.Y., Saltveit, M. (Eds.), The Commercial Storage of Fruits, Vegetables, and Florist and Nursery Stocks. Agriculture Handbook vol. 66. United States Department of Agriculture, pp. 252–254.
USDA, 2015. Agricultural statistics 2015. United States Government Printing Office. Washington, DC. https://www.nass.usda.gov/Publications/Ag_Statistics/2015/Ag_Stats_2015_complete%20publication.pdf.
Van Hauwermeiren, A., Coene, H., Engelen, G., Mathijs, E., 2007. Energy lifecycle inputs in food systems: a comparison of local versus mainstream cases. J. Environ. Policy Plan. 9, 31–51. https://doi.org/10.1080/15239080701254958.
Wang, X., Ouyang, Y., Liu, J., Zhu, M., Zhao, G., Bao, W., Hu, F.B., 2014. Fruit and vegetable consumption and mortality from all causes, cardiovascular disease, and cancer: systematic review and dose-response meta-analysis of prospective cohort studies. BMJ 349, g4490. https://doi.org/10.1136/bmj.g4490 1-14.
Williams, A.G., Audsley, E., Sandars, D.L., 2006. Determining the environmental burdens and resource use in the production of agricultural and horticultural commodities. DEFRA Project IS0205 http://randd.defra.gov.uk/Default.aspx?Module=More&Location=None&ProjectID=11442.
Williams, A.G., Pell, E., Webb, J., Tribe, E., Evans, D., Moorhouse, E., Watkiss, P., 2008. Comparative life cycle assessment of food commodities procured for UK consumption through a diversity of supply chains. DEFRA project FO0103 http://randd.defra.gov.uk/Default.aspx?Module=More&Location=None&ProjectID=15001.
WRAP, 2011. Fruit and vegetable resource maps. WRAP project RSC008. http://www.wrapni.org.uk/sites/files/wrap/Resource_Map_Fruit_and_Veg_final_6_june_2011.fc479c40.10854.pdf.
WRAP, 2012. Reducing supply chain and consumer potato waste. WRAP project RBC820-004. http://www.wrap.org.uk/sites/files/wrap/Amcor%20project%20report%20final%2C%2003%20Jan%202012.pdf.
WRAP, 2013. Household food and drink waste in the United Kingdom 2012. WRAP project CFP102. http://www.wrap.org.uk/sites/files/wrap/hhfdw-2012-main.pdf.pdf.
WRAP, 2014. Toolkit for fresh produce. Screening tool. http://www.wrap.org.uk/sites/files/wrap/WCRE%20Toolkit%20V2.pdf.
WRAP, 2016. Estimates of food surplus and waste arisings in the UK. http://www.wrap.org.uk/sites/files/wrap/Estimates_%20in_the_UK_Jan17.pdf.
Wu, H., Jouhara, H., Tassou, S.A., Karayiannis, T.G., 2012. Modelling of energy flows in potato crisp frying processes. Appl. Energy 89, 81–88. https://doi.org/10.1016/j.apenergy.2011.01.008.
Zarei, M.J., Kazemi, N., Marzban, A., 2018. Life cycle environmental impacts of cucumber and tomato production in open-field and greenhouse. J. Saudi Soc. Agric. Sci. in press. https://doi.org/10.1016/j.jssas.2017.07.001.